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Electric and Magnetic Measurements

and

Measuring Instruments

BY

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PREFACE.

The following volume has been written for the use of those who have to do with electrical and magnetic measurements in one form or another, and as these must be made in practically all branches of the profession, from the simple testing out of lines and resistances to the most elaborate determination of designs, it is hoped that its sphere of usefulness will be quite large.

The subjects have, throughout, been approached with a view toward their use by users, not manufacturers, of measuring apparatus, that is to say the book is in no sense intended as a treatise on the design and construction of instruments, the circle interested being decidedly limited. Descriptions are, however, given of apparatus as well as of methods of test, because knowledge of the manner in which a principle is utilized in concrete instruments often suggests, to one having a determination to make but is at the same time without the particular form of appliance ordinarily employed for that purpose, means of adaping thereto some other device which is at hand. Further, in illustrating examples of instruments for different kinds of work, there has been in mind the idea that these will enable engineers to decide, with the aid of their general engineering knowledge, which are the best suited to their particular requirements.

In line with the general idea of making the volume of value to the profession at large, there has been adopted the use of an appendix which is thought to be novel in character and to which attention is invited. It will be seen by reference thereto that, without cumbering the text with numerous reiterations of manufacturers names or the description of multitudinous instruments of a given class differing one from the other only in minor detail, those who are confronted with the necessity of procuring apparatus for making given tests have provided a convenient means of ascertaining not merely the names but also the addresses of the majority of manufacturers of that particular kind of goods.

Another point which is thought to be novel and useful is the employment in diagrams of connection of the actual word or reference letter that occurs at each point, instead of the more or less conventional symbol therefore plus a reference letter for the text. The author has used this system in his own work for some time past and finds it of decided utility as a time saver in making sketches and in the interest of clearness.

Owing to certain vexatious delays in connection with some of the illustrations, the issue of this book has been deferred for a considerable period after the completion of the manuscript. It is not, however, thought that the developments in the field in the interim have been of sufficient general interest or applicability to warrant revision.

The author in conclusion desires to make acknowledgment of the courteous services of Mr. Townsend Wolcott, who was good enough to read and correct a large portion of the proofs.

F. W. R.

NEW YORK, *November, 1906.*

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ELECTRIC AND MAGNETIC MEASUREMENTS AND MEASURING APPARATUS.

PART I.

CHAPTER I.

DEFINITIONS OF UNITS.

IN order to measure a quantity, condition, or state of matter, we must first have a standard of reference. For although such quantity, condition, or state of one body can be compared directly with the similar property of another body, this direct comparison cannot be extended to three or more of them, unless the property of all the other bodies be referred to the said property of some selected one, in which case the said one becomes, provisionally, a standard of reference. Authorized and commonly accepted standards are called *units;* and as we have here to deal with electrical measurements, definitions of electrical units will be first in order.

UNIT OF RESISTANCE.

When an electric current flows through a conductor of electricity, a resistance to this flow is always offered by the conductor. The amount of the resistance is dependent upon the material of the conductor, its physical condition, geometrical dimensions, temperature, and, under certain circumstances to be treated later, other conditions.

The unit of resistance, with which all other resistances are compared, is that which is offered to a current of uniform strength and constant direction by a column of pure mercury at the temperature of melting ice, having a mass of 14.4521 grams, a constant cross-sectional area, and a length of 106.3 centimeters. This unit is called the *ohm*, and its value as just given is that determined upon by the "International Congress of Electricians," in 1893, and made legal in the United States by Act of Congress in 1894. It is officially designated and commonly known as the "International Ohm" and is the recognized standard to-day. Before the adoption of the "International Ohm" three other standards were in use at various times. The first was the "Siemen's Ohm," this being represented by the resistance offered by a column of mercury having a cross-sectional area of one square millimeter, and a length of one meter. The second unit is that commonly known as the "B. A. Ohm," "B. A." being an abbreviation for "British Association for the Advancement of Science," who proposed its adoption. In it the length of the cylinder of mercury is 104.8 centimeters. The third standard adopted was the so-called "Legal Ohm" (about which, however, there was nothing legal), which was adopted as a temporary standard by an International Committee, in 1882. It is represented by the resistance of a column of mercury having a cross-sectional area of one square millimeter and a length of 106 centimeters, at the temperature of melting ice. As there are many pieces of apparatus, more particularly resistance boxes and Wheatstone bridges, calibrated in the last-named units still in use, the following comparison table is given:

TABLE I.

Siemen's Ohm = .9408 International Ohms.
B. A. Ohm = .9866 International Ohms.
Legal Ohm = .9972 International Ohms.

UNIT OF CURRENT STRENGTH.

The unit of strength of electrical current is called the *ampere*. A current of one ampere strength when passed through a solution of nitrate of silver, under the conditions named in the footnote below, will cause the deposition of .001118 grams of silver per second. This value of the ampere is as defined by the International Congress of Electricians, in 1893, already referred to, and is commonly accepted as the standard to-day.*

---

* The specification for the construction and use of the "Silver Voltameter" used in laboratories as a primary standard for determining current strength is substantially as follows: The voltameter consists in general of a platinum bowl having a diameter of not less than 10 cm. and a depth of 4 to 5 cm., in which is suspended horizontally, by fine platinum wires, a plate of pure silver having an area of about 30 sq. cm., and a thickness of 2 to 3 mm. The silver plate is wrapped around with clean filter paper secured at the back with

It is, however, simply the commercial standard of current, the fundamental standard from which it is derived being ten times as great, and represented by a current of such strength that when passed through a conductor having a length of one centimeter bent into an arc of a circle having a radius of one centimeter, it will attract or repel a unit magnetic pole placed in the center of the circle with a force of one dyne. Later determinations seem to show that 1 ampere flowing through a silver voltameter for 1 second will deposit .001119 grams of silver, instead of .001118 grams, and that the International Congress definition is that much in error. It nevertheless remains in almost universal use.

UNIT OF ELECTROMOTIVE FORCE.

Electromotive force, commonly abbreviated to E.M.F., is the force or stress which sets up or tends to set up a flow of electric current, just as in hydraulics pressure tends to set up a flow of liquid. As the unit there is taken that E.M.F. which, continuously applied in a constant direction to a circuit having a resistance of one ohm, causes current to flow at the rate of one ampere. This unit is called a *volt*, and as defined by the International Congress already mentioned, is represented with sufficient exactness for practical purposes by $\frac{1000}{1434}$ of the E.M.F. at 15 degrees C. of the cell known as the Clark cell, a description of which will be given later (see page 24). It should here be noted that, as the ampere is definitely determined and of a

sealing wax, in order that no detached particles may fall into the platinum bowl. A solution of nitrate of silver, containing about 15 parts by weight of the nitrate to 85 parts of water, is poured into the platinum bowl to a depth sufficient to completely submerge the silver plate. The current to be measured is passed through the voltameter thus formed, entering through the silver plate and departing through the platinum bowl. The bowl is thoroughly cleaned, dried, and weighed before pouring in the solution. After the current of constant strength has been passed through the voltameter for a given period, carefully measured by a good watch, the bowl is emptied, thoroughly washed, and dried with alcohol. It will be found on again weighing the bowl that it has gained in weight, the added weight being that of the pure silver deposited by the action of the current. To find the current in amperes that was flowing, divide the increase in weight measured in grams by the number of seconds that the current was flowing and by .001118.

To obtain concordant results some manipulative skill is required, and the nature of the voltameter renders experiments expensive. For this reason this form is used but seldom outside of the laboratory, and it is not thought that a sufficient number of readers will be interested in the minutiæ to warrant the devotion of further space to this subject.

fixed value, the volt which is dependent on the ampere and the ohm has not, because as before stated the ohm has had different values from time to time. The system under which the volt is measured should hence always be stated. If it is under the old B. A. or the legal system, the value may be converted into the now commonly accepted International volt with the aid of Table I.

UNIT OF CAPACITY.

Any two electric conductors separated by a dielectric, such as air or any other nonconductor, will store up a charge of electricity if a difference of potential be applied to them. The apparatus formed by the conductors and the intervening dielectric is called a condenser, and its property is known as capacity. A condenser is of unit capacity when one volt difference of potential applied to its terminals causes the flow and storing up of the unit quantity of electricity (one ampere for one second, namely, one coulomb). The unit of capacity as just defined is called the *farad.* Being far too large to be conveniently used in commercial work, the microfarad, which is one one-millionth part of a farad, has become the commercial standard for the comparison of capacities of condensers, cables, etc.

UNIT OF INDUCTANCE.

In addition to the ohmic resistance offered to the flow of the electric current, every electric circuit has another property known as inductance which is analogous to inertia in mechanics, and which opposes any change in current strength. This opposition is offered for the following reasons. A conductor carrying an electric current is surrounded by a magnetic field, the paths of whose lines of force are circles concentric with and whose planes are at right angles to the conductor. The strength of the field is proportionate to the strength of the current and varies therewith. If, therefore, the current's strength increases, an additional number of lines of force is sent out by it, and expanding like the wavelets in a pond when a stone is thrown into the water, cut other proportions of the circuit. In accordance with the laws of electro-dynamics, these waves, as they cut the conductor, set up an E.M.F. which is opposite in direction to the E.M.F. causing the current flow, and therefore makes it impossible for the current to reach instantaneously the value due to the E.M.F. impressed upon the circuit.

The unit of inductance is called the *henry*, and is the inductance of a circuit of such character that when the current therein changes in strength at the rate of one ampere per second, there is set up a counter electromotive force of one volt.

OHM'S LAW.

From the definition of a volt above given it is evident that there exists a certain relationship between volts, amperes, and ohms in a given circuit. To state the law more concisely than in the definition: The current flowing through a circuit is directly proportional to the E.M.F. impressed thereon, and inversely proportional to the resistance of the circuit. If we use the letter I to designate current, the letter E to designate E.M.F., and the letter R to designate resistance, the formula expressing this law of relationship is, $I = \frac{E}{R}$. This law is known as Ohm's law and holds good when I is maintained constant in value and direction. Where the value of I or its direction varies, other elements enter which modify this simple relationship, a matter which will be enlarged upon later.

CHAPTER II.

LABORATORY AND COMMERCIAL STANDARDS OF RESISTANCE, CURRENT, E.M.F., CAPACITY, AND INDUCTANCE.

RESISTANCE STANDARDS.

The Mercury Ohm.

As mercury at the temperature of melting ice is a liquid, and, moreover, readily oxidized when exposed to air, it is evident that the only way to make a standard International ohm in accordance with the specifications laid down in the definition is to enclose the proper quantity of mercury in a tube of glass or similar material. The difficulty of preparing such a tube so that the proper length holds the right weight of mercury, of making contact with the mercury at proper points, of obtaining mercury of perfect purity, and of maintaining the whole apparatus at an accurate uniform temperature, together with other minutiæ which must be taken into account if accurate results are to be had, evidently call for considerable care and manipulative skill of the highest order, and prohibit the use of standards so made, except under very exceptional circumstances.

In Fig. 1 there is shown the standard mercury ohm that is used in the Physikalische-Technische Reichsanstalt, in Berlin. The illustration is given to emphasize the bulk and real complexity of this apparently simple apparatus. As can be gathered from the proportions, it is in the neighborhood of six feet long.

Even when a mercury standard ohm is prepared which complies with all of the conditions laid down in the official designation of the unit, we have a piece of apparatus that is only a secondary standard, and not one directly derived from fundamental units of length, mass, and time.

Lorenz Apparatus.

The standard of resistance can be fundamentally derived by means of the so-called Lorenz apparatus, whose method of operation is based on the following principle:

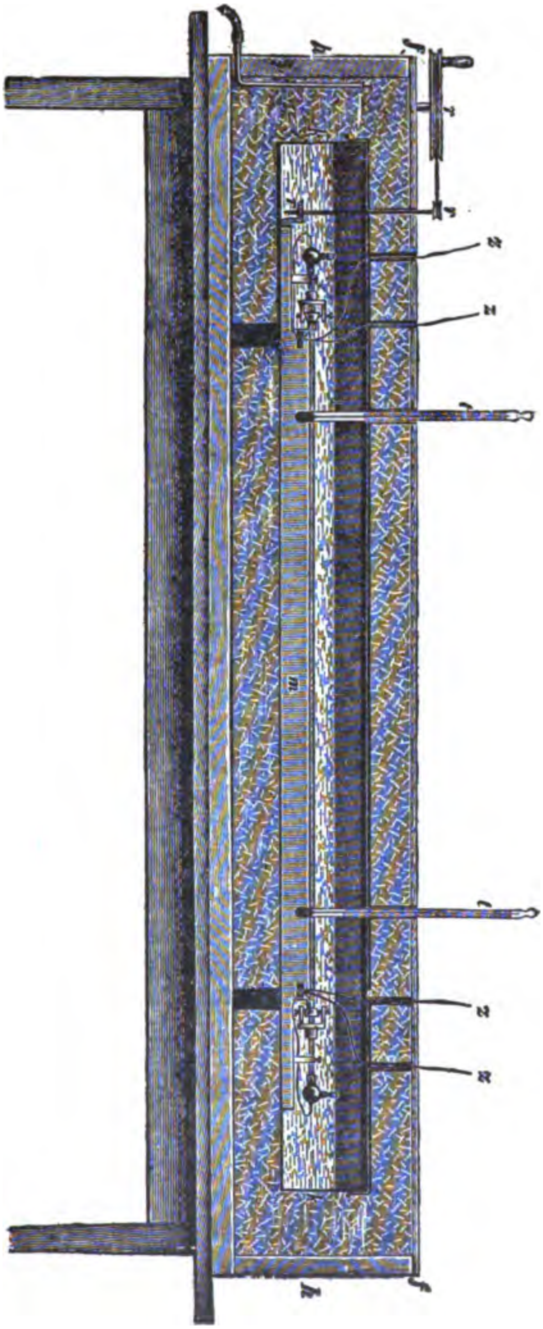

FIG. 1.

Referring to Fig. 2, *SS*, is a coil of several turns of insulated wire, whose diameter is very accurately measured. Mounted co-axially with this coil and within it is a metal disc, *D*, rotating about a shaft, *O*. If current is passed through the coil, *S*, lines of magnetic force flow through the interior of the coil, parallel to its axis and cut the disk, *D*, in consequence of which a difference of potential exists between the center, *O*, of the disk and its periphery. If suitable means of making contact with the center and periphery are provided, that potential can be measured in an external circuit. *PQ* is a bar of resistance metal and *B* a set of batteries of appropriate strength, the whole being interconnected as shown in the diagram. If now current be allowed to flow from the batteries through the coil, *S*, and bar, *PQ*, connected in series therewith, we have a drop of potential along the bar. If *G* be a galvanometer inserted in the circuit through which flows the current due to the difference in potential between the center and the periphery of the rotating disk, and if the terminals of that circuit be attached to the bar, *PQ*, at the points *X*, *Y*, with the positive terminal nearest the positive end of the bar, the distance between *X* and *Y* may be varied until the galvanometer shows that no current is flowing through the disc circuit, in which circumstances the E.M.F. supplied is of course equal to that due to the difference in potential between the points X and *Y* on the bar. Write:

R = resistance between *X* and *Y*,
I = current flowing through the coil and the bar,
M = coefficient of mutual inductance between the coil and the disc,
n = the speed of revolution of the disc,
E = the E.M.F. set up in the disc,

then $$E = MIn$$

By Ohm's law, the difference of potential between the points *X* and *Y* on the bar equals RI, and by hypothesis this also equals the E.M.F. in the disc,

hence, $$E = MIn = RI, \text{ or } R = Mn.$$

The resistance between the points *X* and *Y* can therefore be determined directly by calculation from the geometrical dimensions of the apparatus and from measurement of the speed of rotation of the disc.

It might seem that it would be a very simple matter to measure resistance in this way, but as a matter of fact it is extremely difficult to determine the dimensions of the apparatus with a sufficient degree of accuracy, and almost impossible to measure the speed of rotation as closely as is necessary for accurate work. These physical difficulties are so great that, we understand, what is probably the only Lorenz apparatus on this continent has remained idle for years because no one who has access to it has sufficient leisure or sufficient mechanical skill to get from it results that can be considered as accurate as those derived from a mercury standard.

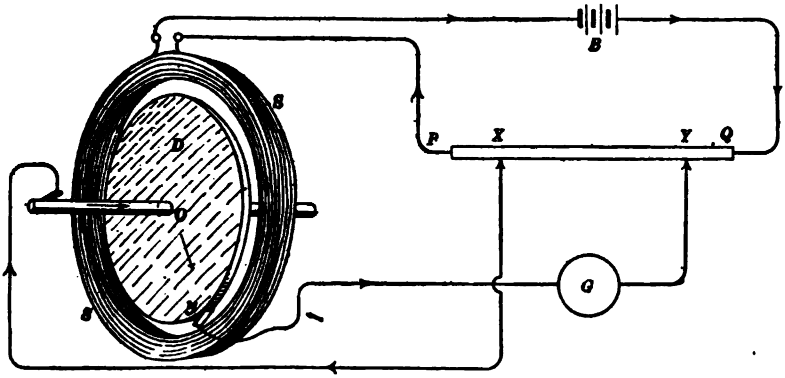

FIG. 2.

Metallic Alloy Standards.

Practically all commercial and the majority of laboratory standards of resistance are formed of wires or plates of high resistance, low temperature coefficient, resistance alloy calibrated by direct or indirect comparison with one of the standards already described. Fortunately, as will be demonstrated later on, electrical resistance can be measured with the highest degree of accuracy more easily perhaps than any other electrical quantity or property, and there are numerous reputable manufacturers who are prepared to supply secondary standards guaranteed to be correct within one fiftieth or even one one-hundredth of one per cent, accompanied, if necessary, by a certificate of this degree of accuracy from national standardizing bureaus. As this degree of accuracy is more than sufficiently good for all commercial purposes, and the value of a properly constructed resistance is very stable, such secondary standards are in universal use in commercial work.

The number of resistance alloys is exceedingly large and the number of trade names for them as varied. Platinum silver, an alloy of one part platinum with two parts of silver, is in extensive use for fine standards, as is also manganin, an alloy of copper, manganese, and nickel. The latter alloy is preferable to the former in that it has a higher specific resistance and a lower temperature coefficient, but it is somewhat oxidizable and must be protected from atmospheric influences by gilding or varnishing, when in the form of small wires or thin sheets. German silver, an alloy of copper, nickel, and zinc, although frequently used in rough commercial resistances, is not suitable for standards because of its comparatively high and somewhat uncertain temperature coefficient. German silver is the name given to a great variety of alloys having the qualitative compositions just stated but differing widely in the quantities of ingredients. Appended Table II gives the properties of several common resistance alloys.

TABLE II.

Alloy.	Resistance per cm.^{3} in C.G.S. unit at 0° C.	Temperature coefficient at 15° C.	Composition in per cents.
Platinum Silver	31,582	0.000243	Pt 33%, Ag 66%
Platinum Iridium	30,896	0.000822	Pt 80 %, Ir 20%
Platinum Rhodium	21,142	0.00143	Pt 90%, Rh 10%
Gold Silver	6,280	0.00124	Au 90%, Ag 10%
Manganese Steel	67,148	0.00127	Mn 12%, Fe 80%
Nickel Steel	29,452	0.00201	Ni 4.35%
German Silver	29,982	0.000273	Cu 50%, Zn 30%, Ni 20%
Platinoid	41,731	0.00031	
Manganin	46,678	0.0000	Cu 84%, Mn 12%, Ni 4%
Aluminum Silver	4,641	0.00238	Al 94%, Ag 6%
Aluminium Copper	2,904	0.00381	Al 94%, Cu 6%
Copper Aluminium	8,847	0.000897	Cu 97%, Al 3%
Copper Nickel Aluminium	14,912	0.000645	Cu 87%, Ni 6.7% Al 6.5%
Titanium Aluminium	3,887	0.00290	

Standards of resistance made of solid alloys take on different forms according to their resistance and the amount of current that they are to carry. For accurate work they must be arranged to be immersed in oil baths, which will keep all of the parts at a uniform temperature, which can be measured by a thermometer that is also immersed in the oil. We will not describe here the old British Association form of standard resistance, as this proved unsatisfactory because of the difficulty of determining exactly the coil temperature. The form adopted by the Reichsanstalt is shown in Fig. 3. The resistance wire, *A*, is heavily insulated with silk and soldered at its ends to the copper terminals, *BB*. The long loop made by the wire then has its two sides brought close together and is wound spirally about the thin brass cylinder, *C*, as shown. This form of winding makes the self inductance very small. The wire loop is purposely made of a somewhat higher resistance than that to which the standard is to be adjusted and is then shunted by a fine resistance wire, whose terminals are likewise soldered to the ends of the rods, *BB*. If the fine wire has, say, one hundred times the resistance of *A* per unit of length, a change of one inch in its length will correspond to a change of one one-

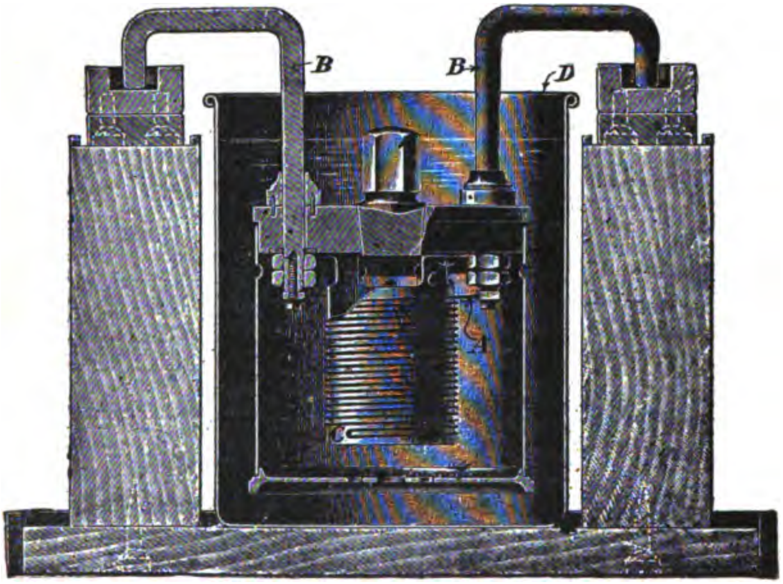

FIG. 3.

hundredth of an inch in the length of the main wire, and very fine adjustments are thus made possible.

The resistance unit as a whole is placed within a vessel, *D*, filled with oil, and the temperature is read off by means of a thermometer placed therein. It is common to supply also a stirring apparatus to keep the oil in circulation, and to insure that all of the parts are of the same temperature.

Resistance standards of a very low value in ohms are usually made of a size sufficient to carry a great deal of current without overheating, as they are ordinarily wanted to measure current in amperes by observing the potential drop in volts at their terminals when the current is flowing. Such resistances often take the form shown in Fig. 4, in which the resistance metal is in the shape of strips or ribbons instead of wires, electrically connected in parallel and sweated into heavy terminal blocks. The use of ribbons exposes a large surface to the air for ventilation, and the end terminals, by their heat-conducting properties, assist in dissipating the heat generated and so keeping the temperature down. A not generally appreciated but very common source of possible error existing in resistances made in this manner is a difference of potential set up between the terminal blocks and the thin blades, by thermo-electric action. These potentials are opposite, and will neutralize each other if the temperatures at both ends of the resistance be the same, but if they be different, due, say, to defective soldering of the blades at one end, there is a resultant E.M.F. at the terminals secured to the end blocks where the drop is measured which is superposed on the drop of potential due to the current flow, so that a measurement of the drop is no longer a correct indication of the current strength. This point is of practical, not merely academic importance, the writer having known errors in excess of ten per cent due to this cause.

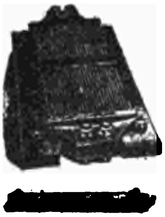

FIG. 4.

When a low resistance is to carry an extremely heavy current and it is undesirable to make the large investment that would be necessary for the air-cooled form just described, a water-cooled type is sometimes employed. This often consists of a tube of the resistance metal equipped with appropriate terminals for connection to the current circuit, and with nipples to which rubber tubing may be attached, and a stream of water at a fixed temperature kept constantly flowing. With this expedient the amount of current that can be handled by the resistance may rise as high as 15,000 amperes per square inch cross-sectional area of conductor without danger of overheating.

Where the resistance standards are to be of high value, say 10,000 ohms or more, the currents that they are to carry are usually very small and give little trouble from heating. The resistances are then formed of very fine long alloy wires wound on spools, as in the case of the Reichsanstalt form above described, but several layers deep. For exact work they too must be immersed in oil, both to keep the temperature uniform throughout and in order that the temperature may be measured; but for commercial work of moderate accuracy this is superfluous. A convenient form of high-resistance box, shown in Fig. 5, contains four coils of 10,000, 20,000, 30,000, and 40,000 ohms respectively. The coils can be used separately or in any desired combination to give a resistance of from 10,000 ohms to 100,000 ohms by steps of 10,000 ohms value. With still higher resistances it becomes necessary to take special precautions in insulating the coil terminals from each other, as otherwise the resistance of the path between them offered by a semi-conducting film of moisture becomes comparable to that of the coils and seriously affects the accuracy.

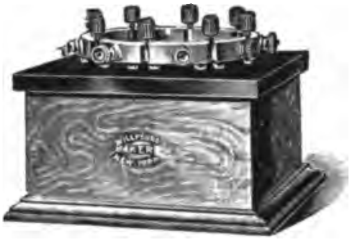

FIG. 5.

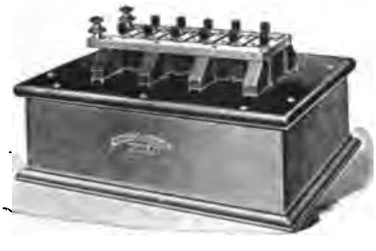

FIG. 6.

A resistance box, containing resistances that may be coupled together to give a total resistance of 1 megohm and provided with special insulating terminals, is shown in Fig. 6. In this, as will be noted, the contacts are supported on tall hard rubber blocks that greatly increase the length of the surface between adjacent contacts over which leakage may take place. This particular box is arranged in ten groups of coils of 100,000 ohms resistance each, which may be interconnected either in series or parallel or any combination of series and parallel. The rubber blocks are so drilled that they do not touch the rods connected with the resistance coils except at the top, thus giving a very long leakage surface.

Such wire resistances of high value are naturally very expensive, and the extreme fineness of the wires frequently causes trouble, because they may become corroded, due to the presence of a small trace of acid or something of that kind. For this reason a resistance made of carbon, often in the form of a streak left by a soft pencil when drawn over ground glass, is frequently employed when a resistance having a value in the order of a megohm is to be constructed. Such a resistance is shown in Fig. 7. The "carbon megohms" are not celebrated for their constancy, however, and it is always advisable before using one to compare it with a wire standard having a resistance of 10,000 ohms, or preferably of 100,000 ohms value by one of the methods to be described presently, in order to determine that it has not deteriorated.

FIG. 7.

CURRENT STANDARDS.

The Voltameter.

In the definition of the ampere given on page 2 there is stated the method of determining the ampere by means of the silver voltameter. This device, however, is but seldom used outside of a laboratory, both for the reasons named and because the cost of the materials entering into its construction, when of a size suitable for measuring currents of some magnitude, is almost prohibitive. The copper voltameter, in which the two electrodes are of copper, and the solution of copper sulphate, gives, when handled with reasonable skill, results that are more than sufficiently close for all commercial purposes. The copper voltameter is easier to manipulate, and the deposit on the plate through which the current leaves the device is strongly adherent; whereas in the silver type the deposit is very apt to be loose enough to be washed off when the platinum bowl is being cleaned preparatory to final weighing, unless a very large surface has been allowed per unit of current. The copper voltameter can, further, be satisfactorily used with current density, namely, current per unit of area of plate surface, about five times as great as that permissible in a silver voltameter, so the former type is much more compact.

A serviceable copper voltameter may be made as follows: A containing vessel, usually of glass, is selected of sufficient size to hold all the plates. Into this is poured a solution of sulphate of copper made by dissolving crystals of pure sulphate of copper in distilled water, with the addition of a small amount (about 1 per cent), of sulphuric acid. It is essential that the solution should be sufficiently acid to turn blue litmus paper red. The solution should have a specific gravity of about 1.15, but this may be as low as 1.1 or as high as 1.2 without vitiating results. The voltameter plates of pure electrolytic copper are immersed vertically in this solution. The plate through which the current leaves the voltameter must be carefully cleaned, dried, and weighed before being placed in the cell, in order that the gain in weight may subsequently be determined, and the strength of the current flowing calculated therefrom. Where large currents are to be handled several positive and negative plates may be used to advantage, they then being interleaved like the plates in a storage battery cell. No more than one ampere per 10 sq. cm. of surface should be passed out of the negative plates, namely, the ones through which the current leaves the voltameter, and the positive plates, through which the current enters, should afford twice this area for the same current. The copper plates should preferably be arranged with one or two short strips or lugs left attached above, so that the current may be led to and from them, instead of leaving the whole plate width to emerge through the surface of the solution, and these lugs should be of as small an area as is consistent with their properly performing their functions. All corners and edges of the copper plates should be rubbed off with sandpaper before the initial measurement is attempted. Where very large currents are to be handled the plates may be corrugated, so as to present a larger area for a given sized plate;

but in this event it is more difficult to determine with certainty that the plates are clean and in condition for use before being placed in the voltameter.

The copper voltameter gives results that are dependent both on the temperature of the solution and on the current density employed. The following Table III, taken from the *Electrician*, London, gives the electrochemical equivalent of copper for various conditions of temperature and current density, and the values there given must be used if accurate results are to be had.

TABLE III. — *Values by Meikle.*

Square Centimeter of Cathode per Ampere.	Temperature.		
	12° C.	23° C.	28° C.
50	.0003288	.0003286	.0003286
100	.0003288	.0003283	.0003281
150	.0003287	.0003280	.0003278
200	.0003285	.0003277	.0003274
250	.0003283	.0003275	.0003268
300	.0003282	.0003272	.0003262

All voltameters are more or less objectionable for use in determining the ampere, for two reasons. First, they are merely more or less reproducible copies of a device which the International Congress thought suitable for the accurate measurement of current strength, but which does not involve determination from fundamental physical units. Second, they involve, in addition to the element of current strength, that of time, and a current must be kept of strictly uniform value for a considerable period in minutes in order to obtain results. In other words, the voltameter gives the average value of the current that has been flowing through any circuit for a given length of time, but does not show the instantaneous values.

The Tangent Galvanometer.

The definition of the absolute unit of current strength states that this is represented by a current of such value that when passed through a conductor having a length of 1 cm. bent into the shape of an arc of a circle having a radius of 1 cm., it will attract or repel a unit magnetic pole placed at the center about which the radius is drawn with a force of 1 dyne. It is hardly feasible to make an instrument for the absolute measurement of current based on this principle, but the unit may be derived from fundamental measurements of length, mass, and time in other ways.

One of the oldest devices for the accurate determination of current strength is the tangent galvanometer, which is an instrument in which a magnetized needle assumes a position determined by the resultant of the action thereon of the earth's magnetic field at a given point, and the magnetic force due to a coiled conductor through which flows an electric current. The strength of the earth's magnetic field at any point may be determined to practically any desired degree of accuracy by means of a cumulative method, which need not be enlarged upon here. By suitably proportioning the diameter of the coil of wire to the length of a magnetized steel needle suspended at its center so as to be freely rotable, the force with which the current tends to deflect the needle by reason of the magnetic field surrounding the conductor will vary in direct proportion to the strength of the current.

Without going too deeply into theory the action may be understood from the following: In Fig. 8, let the length of the line, *OA*, represent the magnitude of the force due to the earth's magnetism tending to restrain the needle, and the direction of the line represent the direction in which it tends to hold it, and let the line *OB*, in a similar manner represent the magnitude of the force exerted on the needle by the current flowing through the coil and the direction in which it tends to hold it. This direction is made to be at right angles to *OA*, by placing the tangent galvanometer in such a position that the earth's field holds the needle at right angles to the plane of the coil when no current is flowing. From the law of the parallelogram of forces the resultant of the two forces, *OA* and *OB*, acting on the needle will cause it to assume the direction *AB*.

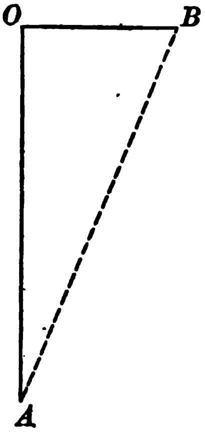

FIG. 8.

OB, representing the strength of the current, is the tangent of the angle *OAB* through which the needle has moved, and therefore the tangent of the angle of deflection of the needle is a measure of the current strength. The strength of the magnetic needle is of no consequence, as, if it were increased, the action on it of the magnetic field due to the current and that of the earth's field would be increased alike, and if decreased, decreased alike, the angular deflection remaining the same for a given current as long as the strength of the earth's field remains constant.

Tangent galvanometers are of value in that they enable us to derive fundamentally the unit of current strength; but they are in very limited use, as we have forms of secondary standards of satisfactory accuracy and more convenient of manipulation. Moreover, it is necessary to place tangent galvanometers in very inaccessible locations in order that the directive action on their needles due to the earth's field may not be seriously and constantly disturbed, in ever changing degree, by the other magnetic fields due to electric currents such as are in use in every civilized community.

The Ampere Balance.

A different class of apparatus in wide use as a standard for the measurement of electric current is the ampere balance, the most generally known example of which is that invented by Lord Kelvin. While this must primarily be calibrated with the aid of a silver or copper voltameter, or a tangent galvanometer, it contains no parts liable to change under proper usage, and has the great advantage that it indicates the current's strength at every instant, not the product of the average current by the time that it has been flowing as in the case of the voltameter. It is, further, simple of manipulation considering that it is a standard. The apparatus is based on the well-known law that currents flowing in the same direction in parallel adjacent conductors attract each other, and those flowing in opposite directions in parallel adjacent conductors repel each other, and that the forces of attraction and repulsion at a given fixed distance are in direct proportion to the squares of the strength of the currents.

It is evident that in an apparatus embodying this principle one of the conductors must be freely movable in order that any tendency to change in relative positions may at once be observed by suitable means and equilibrium restored by the application of appropriate restraining forces. There is some difficulty in providing a means for making electrical connection with a movable conductor which will carry considerable current and at the same time be perfectly flexible. In the Kelvin apparatus this problem was solved as follows: Referring to the diagrammatic perspective in Fig. 9, *T* and *T′* are pairs of semi-cylinders of brass, the upper ones of which are rigidly secured to the base frame of the instrument. To the upper surfaces of the upper pairs far back from the edge are soldered a large number of exceedingly fine copper wires, which are combed out to be parallel with each other and then led over the rounded surfaces of the upper semi-cylinders, across the short gap separating them from the lower semi-cylinders and nearly around the latter where they are finally soldered in place in a similar way. These fine wires, or ligaments as they are called, serve both to sustain the movable conductor and as a means of conveying the current. Their flexibility alone would enable the coils of wire, *MM′*, to swing about the point of suspension with perfect freedom; but making the surfaces cylindrical gives an additional factor of assurance that there shall be no restraining due to the bending of the ligaments, in that the cylinders allow a kind of rolling motion which greatly decreases any opposition to motion that the almost inappreciable rigidity of the ligaments might tend to offer.

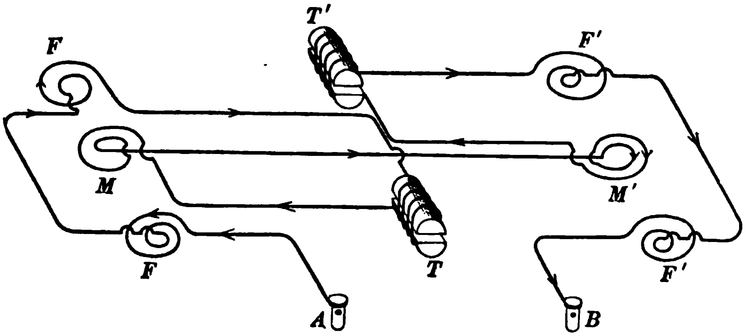

FIG. 9.

Having now a pair of coils, *MM′*, at the opposite ends of a freely suspended lever and through which current may be passed, all that is necessary in order to have the elements of a complete measuring instrument is a set of stationary coils similar to the freely suspended ones and placed parallel thereto, together with a suitable measurable restraining force to keep the movable coils in a position of equilibrium when current is passed. In the actual instrument, two stationary coils are used in connection with each movable one; all being interconnected so that at the right-hand end of the apparatus the reaction between the upper stationary coil and the movable one tends to move the latter in one direction and the lower stationary coil assists in that action, the stationary coils on the other end of the apparatus being coupled in a reverse manner, the sum total of all of the efforts thus being to cause the lever to go downward at one end or the other. In the figure, the connections are such that the left-hand end of the balance tends to rise when current is applied. As the direction of current flow is opposite in the two halves of the instrument, it can be seen that if the whole apparatus is placed in a uniform magnetic field, such as the earth's field, the results will not be vitiated; as any tendency to a decreased or increased effort on one arm of the balance, because of the presence of that field, is offset by the decreased or increased force exerted by the other half. An apparatus that is made independent of the influences of outside magnetic fields, by composing it of halves equally and oppositely affected by such fields, is said to be astatic.

The measurable restraining force applied to hold the movable element of the balance in a position of equilibrium is supplied by a movable weight, whose distance from the fulcrum of the balance arm is adjustable. An index finger is attached to the movable element, so that its position relative to a fixed mark may be observed and the fact that equilibrium exists established. These details are shown in Fig. 10 where I is the index finger, D the fixed scale, and R the movable weight sliding along the movable arm, P. Only one of the trunions, T', supporting the movable arm is shown. It will be noted from the illustration that the apparatus is provided with two scales, one of them having equally spaced divisions and the other in which the spaces between the scale markings progressively increase in size from zero on. The equal scale shows the distance that the movable weight, R, has been moved and the non-equal one, the current's strength, which can thus be read off directly from the position of the weight. It will be noted that the zero of the scales is not in the center, as would be the case if the ordinary mechanical balance arrangement were employed, but at the extreme left-hand end. This feature is made possible by the following plan: At the right-hand end of movable element there is secured the trough, *A*, in which is placed a certain definite weight that is just sufficient to counterbalance the weight of the movable piece, *R*, when that piece stands at zero on the scales. During that part of the path of *R* included between the zero and the point opposite to the fulcrum, *R* is opposed to the weight placed in *A*, and their difference is the force balancing the pull of the current. At the center of the scale, the opposing force is that due to the weight in *A* only, and from that point on to the extreme right-hand end of the scales that due to the sum of the moments (weight times distance from the fulcrum) of *R* and *A*. The scale that is not equally divided is attached to the stationary portion of the instrument, and from it ampere values may be read off directly. The equally divided scale is part of the movable balance arm, and is supplied because it is easier to estimate correctly the value of a fraction of scale division when all divisions are of uniform value than of a division in a series which is progressively increasing or decreasing. The latter scale is used only when

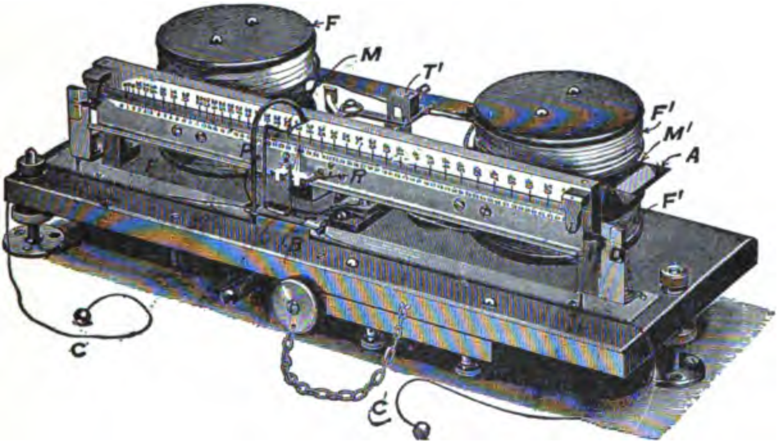

FIG. 10.

exact measurements are to be made, and the value of the current then computed with the assistance of tables that come with the instrument and which give the doubled square roots directly.

The balances are provided with glass covers to shield them from draughts, and the movable weight, *R*, is slid along the balance arm through the aid of a carriage, *B*, which may be operated from outside by means of silk cords, *CC*, the whole being so arranged that no part of the weight-moving device is in contact with the weight when the cords are released, thus obviating any chance of error due to friction between the pusher and the weight. These balances are made in a variety of sizes suitable for measuring currents as low as .025 amperes to as high as 2500 amperes. They are particularly valuable in that they may be used to measure alternating currents as well as direct currents, the wire windings in the large sizes being composed of cables of many fine insulated wires in parallel, so as to insure proper and uniform distribution of current irrespective of inductive influences.

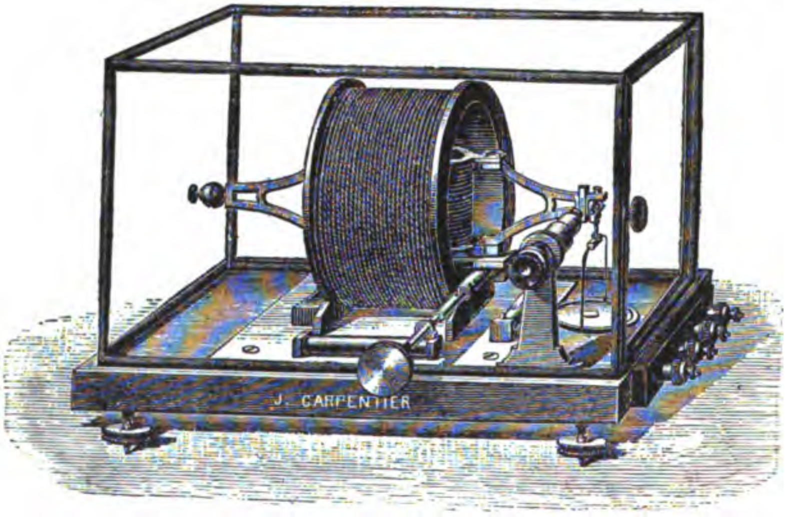

FIG. 11.

It has become of late the fashion in some quarters to ridicule the Kelvin balances because they are somewhat tedious to manipulate as compared with direct reading meters of commercial patterns to be described in a latter chapter, because they are not portable, and because it takes some time for a balance to be obtained, as the period of oscillation of the movable element is very long, approximately three or four seconds. It is true that all of these objections exist; but, on the other hand, the apparatus contains no parts liable to change, except the windings themselves, which might deteriorate if heavily overloaded, they have exceptionally long scales, they are astatic, and good on both direct and alternating current. The latter quality renders them specially valuable in the accurate measurement of alternating current by transfer methods and in the calibration of alternating instruments.

Other forms of balances have been devised from time to time, notably, the Pellat balance, shown in Fig. 11. In this there is but one stationary and but one movable coil which are arranged at right angles to each other. The current is led into and out of the latter through fine spirals of silver, which afford but little opposition to its movement, and a scale pan with weights is used to supply the restraining force.

The Potentiometer.

Another method of accurately measuring a current is to pass it through a known standard resistance and measure the resultant drop in potential. If the current is continuous the most suitable instrument for this method of measurement is the potentiometer. As a special chapter (see page 73) has been devoted to this instrument and its uses, the reader is referred to it for a description of this very satisfactory method of current measurement.

ELECTROMOTIVE FORCE STANDARDS.

Determination by Drop of Potential.

The definition of the volt suggests a practicable method of establishing this unit. We have only to pass a current of known strength through a known standard resistance when the difference of potential at the terminals of the resistances can be calculated from Ohm's law, $E = RI$. In measuring E.M.F. in this way, it must be borne in mind that unless the device that indicates the voltage is of practically infinite resistance, R in the formula is not the resistance of the standard resistance coil but that of the circuit formed by the coil shunted by the measuring apparatus attached to its terminals. In Fig. 12 herewith, let *B* represent a source of current, and *A* represent a balance or other device for accurately measuring the current strength, *R* the standard resistance, whose value may be assumed to be one ohm, and *V* the device that indicates the voltage. When *V* is not attached to *R*, the difference of potential between the terminals *r* and *r'* of the latter, when one ampere is flowing, is from Ohm's law, one volt. Assume that the resistance of *V* is 49 ohms. If this is now connected to the terminals of *R*, the resistance between the points *r* and *r'* is no longer 1 ohm, but from the law of divided circuits (see page 93) .98 ohm, and the difference of potential with one ampere flowing .98 volt instead of one volt, or an error of 2%. Therefore, if *V* is of a resistance comparable with that of the standard resistance coil, the value of its resistance must be known and allowed for, in accordance with the above illustration. With the aid of the potentiometer, measurements may be made without necessitating this correction, as will develop later in the chapter devoted to this instrument.

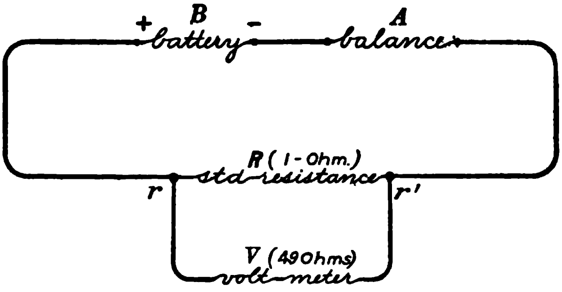

FIG. 12.

Standard Cells.

The Clark Cell. — According to definition the International volt is an E.M.F. whose value is represented with sufficient accuracy for practical purposes by $\frac{1000}{1434}$ of the E.M.F. between the terminals of the battery known as the "Clark Cell." The Clark cell is one in which the negative electrode is a pure zinc rod or amalgam of zinc and mercury, the positive electrode pure mercury, and the electrolyte a saturated solution of pure mercurous sulphate and zinc sulphate. Many precautions must be taken in the preparation of the materials forming this cell so that they may be of sufficient purity, and considerable skill is required in putting such a cell together. As they may be purchased from numerous manufacturers who have the requisite facilities, the detailed instructions for constructing them will not be given here. Those who are interested may refer to the report of the International Congress which selected the cell as a standard, or the fairly complete abstracts which will be found in Fleming's "Handbook for the Electrical Laboratory and Testing Room," Carhart's "Electrical Measurements," etc. The cell is usually set up in small glass tubes having a diameter of about ⅝ of an inch and a depth of 1½ to 2 inches, the elements being often arranged as shown in Fig. 13. This is the original form of the Clark cell, and is objectionable for the following reasons: It is not portable, as its inversion would cause the mercury to contaminate the zinc, the electrolyte must be kept concentrated, and when the temperature rises it takes a considerable length of time for the solution again to become saturated. The latter fault is particularly serious, as it means that there is a lag of several hours, or perhaps days, before the E.M.F. will correspond with that of a normal cell at the new temperature.

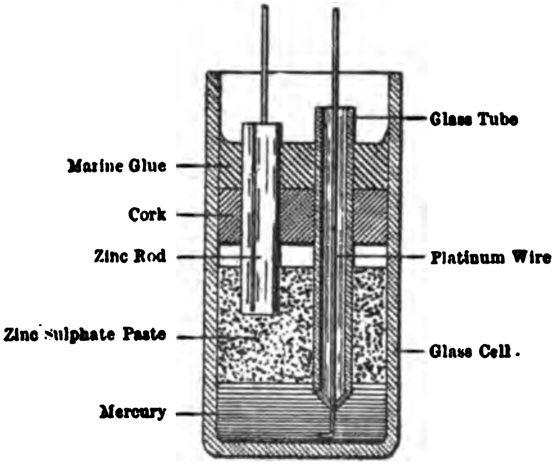

FIG. 13.

To insure that all portions of the cell may quickly attain any new temperature, Mr. Hamilton has adopted the expedient of precipitating chemically a thin film of silver on the outside of the glass containing tube and then heavily plating this coating with copper. Copper, of course, is an excellent heat conductor, and since it is in such intimate contact with the glass, the attainment of a new temperature throughout the cell is greatly accelerated.

The difficulty due to the presence of a large mass of free mercury may be overcome by the use of an electrode which consists of a flattened spiral of platinum wire amalgamated, either by electrolytic methods, or by heating to redness and plunging into mercury. By virtue of capillary attraction this spiral will take up and hold enough mercury between its convolutions to make it an excellent electrode. It performs its function so well that the tube may be inverted or even sent through the mails without shaking any of the mercury loose. The use of such amalgamated spirals is due to Dr. Muirhead. A cell of this form, according to the International Congress, has an E.M.F. of 1.434 true volts. If, however, we use the later and more generally accepted chemical equivalent of silver, .001119, instead of .001118, as used by the said Congress in defining the value of the ampere, the E.M.F. of the Clark cell is 1.4327 volts, a value which is now used abroad and is probably more nearly correct.

Another form of cell better than the original Clark cell is a modification devised by Professor Callender, which is often called the Inverted Clark Cell. In this the order of the elements entering into the construction is reversed and the lag between the temperature of the cell and the E.M.F. is nearly absent.

The Carhart-Clark Cell. — The Carhart-Clark cell, a form that is widely used in this country, is shown in section in Fig. 14. The figure shows a globule of metallic mercury used for one pole, but it is not uncommon to use the amalgamated platinum spiral described above. The paste of mercurous sulphate is separated from the zinc by a wad of asbestos on which the zinc rests. The most important change from the original Clark form is in the use of a zinc sulphate solution that is not kept saturated at all temperatures, but on the contrary is saturated only when the temperature falls to 0° C., at which temperature no cell is ever used in practice. No time is therefore expended in waiting for the solution to become saturated if the temperature should rise, and there is no consequent increase of solution density that lowers the E.M.F. This cell not only responds far more quickly to temperature changes, but has a lower temperature coefficient which figures out just about one half of that of the original Clark form. Professor Carhart gives the formula connecting the temperature and E.M.F. as

$$E_t = 1.440\{1 - .0004\,(t - 15)\},$$

this being correct at temperatures around 15° C.

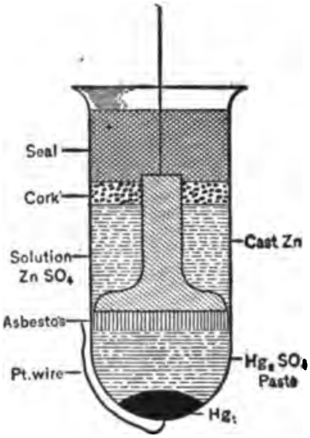

FIG. 14.

A drawback to these and all other standard cells containing non-saturated solutions is that, if improperly sealed, the evaporation of the liquid causes a change in concentration, with a resultant change in E.M.F.

Cadmium Cells. — The comparatively high temperature coefficient of the Clark cell led many experimenters to investigate other combinations that would be equally reliable, but in which this drawback would be less prominent. The best is probably that patented by Weston (U. S. Patent No. 22,482 of 1891). It is similar in all respects to the Clark cell, except for the fact that cadmium is used instead of zinc and cadmium sulphate instead of zinc sulphate. According to the specifications, this cell has a temperature coefficient of but .018 per cent per degree C., this being only one fourth of the temperature coefficient of the Carhart-Clark cell, and one eight of that of the original Clark cell. Its E.M.F. is given as 1.019 volts. The Reichsanstalt in Berlin have carefully tested this type of cell and recommend the form shown in Fig. 15. Its H-shape is that suggested in 1885 by Lord Rayliegh for the Clark cell, and frequently used for that purpose. The preparation of the materials and the assemblage of the cell calls for the same minute observation of details, as is the case with the Clark cell in any of its forms.

Care and Use of Standard Cells. — Standard cells form a most valuable basis for the accurate measurement of potential and current for both laboratory and commercial conditions, and they should be more generally used than they are. It is not recommended that the user attempt to make his own, in fact the results in that event would probably be very unsatisfactory, but the cells themselves, as before stated, can be easily and inexpensively purchased in many quarters. They are by no means the delicate fussy devices that they have somehow the reputation of being; on the contrary, they are really very rugged and will stand an incredible amount of misuse without injury. The writer has even known of one being dead-short circuited for an appreciable interval, certainly as long as two minutes, after which the potential, although at first far below normal, rapidly rose, and after the expiration of several hours again became normal. The power of the form in which the amalgamated platinum spiral is used to withstand tumbling about has already been mentioned.

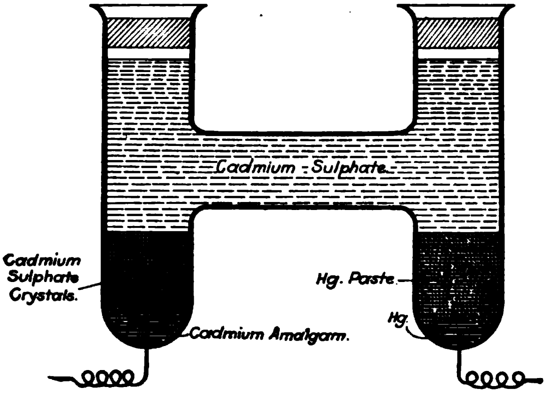

FIG. 15.

It must always be borne in mind that these standard cells give their stated E.M.F. only on open circuit, namely, when not delivering any current. When, therefore, they are attached to the terminals of a commercial form of voltmeter (all of which, as explained further on, require current for their operation), the resulting indication will be meaningless. Students seem to be particularly prone to attach a standard cell to the low-reading coil of a commercial voltmeter having a resistance that is almost as low as that of the cell itself, with the result that the voltage indicated by the instrument will steadily and rapidly continue to fall until nearly zero because of the polarization due to the current output that is demanded. To guard against this abuse it is usual to build into the base of the case containing a standard cell, such as is shown in Fig. 16, a high resistance of a value of at least 10,000 ohms, connected permanently between one battery terminal and its binding post, so that it is impossible under any circumstances to dead-short circuit the apparatus.

The device that is almost always used for determining E.M.F. in terms of the E.M.F. delivered by a standard cell is the potentiometer. With this the E.M.F. is measured when the cell is not delivering current; all of which will be explained in greater detail in the chapter devoted to that instrument.

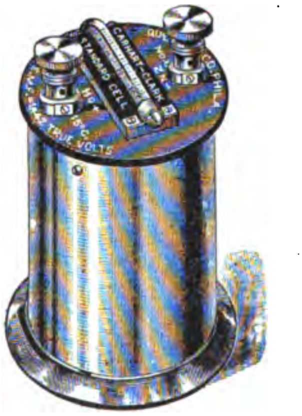

FIG. 16.

The Daniell Standard Cell. — In the event that a Clark cell is not available, the ancient and honored copper, copper sulphate, zinc sulphate, and zinc Daniell cell can be made up as a standard having no mean pretension to accuracy. To make one there is required a glass-containing vessel, usually an ordinary batter jar, a small porous cup (say two inches in diameter by four inches deep), a rod of commercially pure zinc carefully cleaned with sandpaper and subsequently amalgamated with mercury, a strip of pure electrolytic copper of any convenient dimensions (say one inch broad and five or six inches long), a solution of chemically pure zinc sulphate of a specific gravity of 1.200 (555 parts by weight of zinc sulphate crystals to 445 parts of distilled water will give this density), and a saturated solution of chemically pure copper sulphate in distilled water with the copper sulphate present in excess. Both the zinc rod and the copper strip must, of course, be provided with suitable terminals for the attachment of the circuit wires. It is advisable to plate the copper strip with a coating of electrolytic copper just before using it, either by making it the anode in a regular plating bath or by short circuiting the cell on itself, in which case the copper plate becomes automatically coated with electrolytic copper.

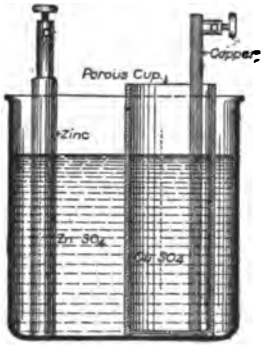

FIG. 18.

The copper strip is placed in the porous cup and the cup is almost filled with the copper sulphate solution. The porous cup is then placed in the glass-containing jar and the zinc solution poured around it until the level of its surface is practically on the same plane as the level of the copper sulphate in the porous cup. The zinc rod is then placed in the zinc sulphate solution, and the cell as a whole is ready for use.

Such cells have an E.M.F. of 1.072 volts, and are of extremely low internal resistance so that they may furnish an appreciable amount of current. They do not polarize readily, and have a very low temperature coefficient. With reasonable care in selecting the materials, these cells may be relied upon to be accurate within about one fifth of one per cent. A cell of this kind is shown in section in Fig. 18.

Electrostatic Voltmeters.

Referring to Fig. 19, if *aa* be two box-shaped metallic sectors, *bb* a movable paddle-shaped conductor, and a difference of potential be applied between conductors attached to the two, we have the following conditions:

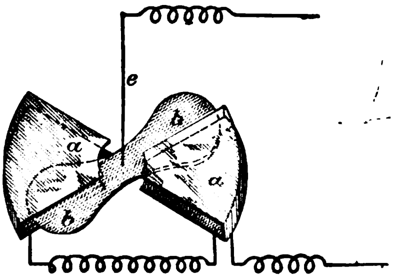

FIG. 19.

The instrument is a condenser, the double-ended sector, *bb*, forming one coating, the dielectric being air and the outer coating being the stationary sectors, *aa*. When the difference of potential is applied between the inner and outer coatings, the former, being movable, tends to rotate with a force proportional to the potential about its axis, *e*, in order that it may place itself in a position where the capacity of the condenser is a maximum;

in other words, to turn until it is completely enshrouded by *aa*. This force is resisted by the torsional elasticity of the metallic suspension fiber, *e*, and the resulting deflection is therefore a measure of the applied voltage.

Instruments for the measurement of E.M.F., based on this principle, are called electrostatic voltmeters or electrometers. Although they are in somewhat common use abroad they are not as well known or as much relied upon in this country as standards for the measurement of potentials.

The deflectional forces are small as compared with those existing in some other types of instruments, so it is necessary to suspend delicately the moving element, and even then they cannot be used for the measurement of very low potentials. On the other hand, they are entirely independent of temperature, can be used on either direct or alternating current, are not influenced by magnetic fields, consume no current, and, in fact, with the exception of the possibility of an error caused by adjacent electrostatic influences (from which, however, it is possible to shield them by a grounded metallic casing), their deflections with a given potential depend only on their geometrical dimensions and the elasticity of the suspending fiber. The latter can be made a very constant and reliable quantity by selecting a length of the fiber such that the stress in it, due to its being twisted, is but a small fraction of the limit of elasticity. Electrostatic voltmeters may therefore be made as acceptably reliable standards.

Where the voltages to be measured are comparatively low, of, for instance, an order of 100 volts, sufficient deflectional force is obtained by superimposing several sets of charged rotatable vanes swinging between a corresponding number of stationary charged plates. Instruments so constructed are multicellular electrostatic voltmeters, and one of them of a commercial type is shown in Fig. 20, this being an illustration of the Kelvin meter. In this, voltage is indicated by a needle that sweeps over a suitably graduated scale, and the indications are damped by a disk attached to the movable portion and moving in a vessel containing oil that is inserted in the lower part of the instrument, as shown by the partially broken away part in the figure. In the laboratory standard type of this instrument, a small mirror is attached to the moving system, and by means of a beam of light thrown on it and reflected to a fixed scale, the equivalent of a very long needle is obtained, which enables one to read the indications with a high degree of accuracy. The Board of Trade standard laboratory in London has a set of electrostatic voltmeters of this class, one of which is shown in Fig. 21. These have no numerically divided scales, but only two reference lines, one of which shows the position of the moving element when no current is applied, and the other when a certain potential, such as 100, 500, 1000, etc., volts, is applied. In the illustration the metallic hood covering the instrument is shown as removed and placed at one side of the apparatus. To shield against foreign electrostatic charges this cover when in place is grounded. The indications of this instrument also are damped by means of an oil cup. It is claimed that the electrostatic voltmeters at the Board of Trade laboratory give indications that are accurate within one part in 3000.

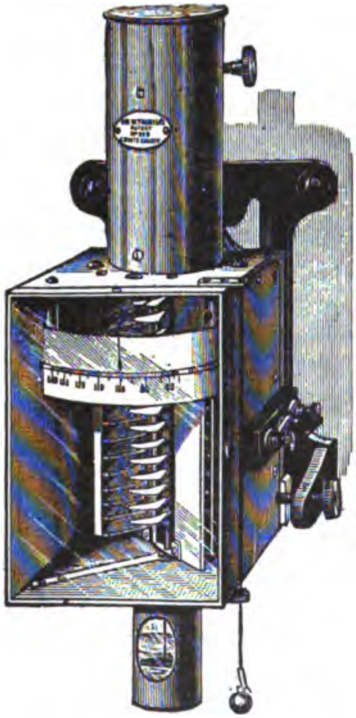

FIG. 20.

Volt Balances.

From Ohm's law, the current passing through a circuit is directly proportional to the voltage applied, if the resistance of the circuit be kept constant. If, therefore, we take any current-consuming instrument that would ordinarily indicate amperes, having a resistance sufficiently high so that the current drawn would not pull down the E.M.F. of the source to be measured, or to heat the conductors forming the instrument sufficiently to alter its resistance, the indications of the instrument will vary in proportion to the applied voltage, and the scale may be divided to read volts instead of amperes. The Kelvin Centiampere Balance, designed to measure currents varying in value from .01 to 1 ampere, is frequently used as a standard voltmeter on this principle, by inserting in series with it a properly adjusted known high resistance, that may be obtained from the makers. The value of the resistance is made such that the values indicated by the movable rider on the balance indicate volts directly, or else some simple multiple, such as one half, one tenth, etc., of the numerals in volts. The measurement of potentials in this way depends, as above stated, on the assumption that the resistance of the instrument remains constant during the test. As copper, the material of which the wire coils of the balance are formed, has a resistance that varies quite markedly with a change in temperature, it is necessary, where accurate results are required, to correct for such changes of temperature. For this purpose, the temperature is observed by a thermometer, which is inserted as close as possible to the coils.

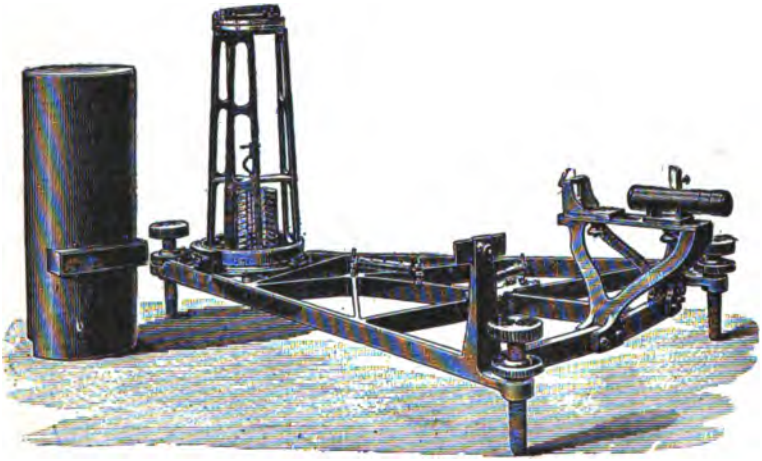

FIG. 21.

STANDARDS OF CAPACITY.

As has been stated on page 4, capacity is the property by virtue of which two electrical conductors, insulated from each other, will store up a quantity of electricity, if a difference of potential be applied to them. The amount of charge depends on the area of the opposing surfaces, on the distance between them, and the nature of the intervening medium; namely, whether this be air, glass, mica, or paper, or any other substance. Such a device for storing up an electric charge is called a "condenser."

Condensers that are to be used as standards are often constructed so that the dielectric intervening between adjacent sides is air, and the spacings between the plates are kept constant by a rigid mechanical construction. The capacity of such standards is determined by measurements involving the elements of current strength and time in one of the ways described in Chapter VIII, and may then be used for purposes of comparison. The construction of the standard Kelvin air condenser is shown in Fig. 22.

Condensers in which air is the dielectric are bulky because of the mechanical construction, and heavy because the plates must be made thick enough to support themselves. It is possible to make a form which is as satisfactory as regards permanence, and far lighter and more compact, by using mica as the dielectric. The ordinary construction in such cases is to make the conductors of strips of tinfoil with mica plates intervening. However, unless the pressure holding this aggregation of mica and tinfoil assembled together is kept rigorously constant, the capacity will vary, due to the fact that the dielectric between the adjacent tinfoil coatings is a varying thickness of air and mica instead of a constant thickness of mica alone. To minimize trouble on this score, the condensers are usually well soaked in paraffine, which effectually prevents the entrance of air and makes a more or less solid mass. A much more satisfactory expedient, however, is that used by Mr. Hamilton, in which a thin film of silver is chemically precipitated upon,

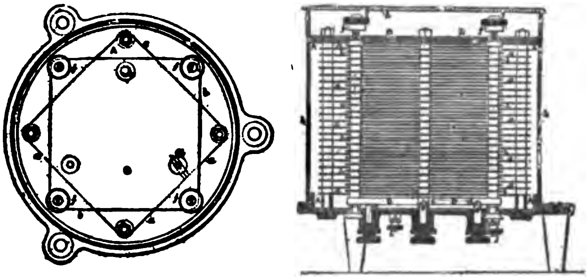

FIG. 22.

and strongly adheres to the mica plates. The coatings on each side of a plate, with the intervening mica, form a condenser of small capacity. By assembling a sufficient number of these small condensers in one case, and interconnecting them, a condenser of any required capacity may be formed. The final adjustment is made by utilizing the fact that the sheets of mica vary in thickness, and consequently the capacities of the different elements are different, together with the principle that series connection of two or more elements reduces the capacity of the whole. Having some extra elements, a few substitutions of thick for thin ones, or *vice versa*, will bring the capacity at least pretty closely to the desired magnitude, and if the exact value cannot be reached in this manner, it may be reached either by connecting some elements in series or by scraping away a part of the coating from some of the plates. Such condensers are fully as reliable as the air form, and may be used as standards with equal confidence. It is stated that their accuracy will change less than one part in one thousand, even after taking apart and reassembling.

Condensers have temperature coefficients, that is to say, their capacity varies to some extent with changes in temperature, so that in comparison methods of measurement, the temperatures of the standard, and unknown condensers must be taken into consideration.

STANDARDS OF INDUCTANCE.

As in the case of capacity, inductance is a property of an electrical circuit, which is defined in terms of more fundamental units, namely, the volt, the ampere, and the second, and standards are prepared by making up a circuit having inductance, measuring that inductance by one of the primary methods described in Chapter IX, and afterwards, if desired, using it for comparison purposes when making measurements involving the use of a comparison standard. According to the definition of inductance, this property depends on having the magnetic lines of force which surround a current-carrying conductor cut another conductor or another portion of the same one. A standard that is economical of manufacture, compact, and efficient must therefore have its elements arranged so that this cutting action is a maximum. This condition will exist when a conductor is wound up into a form of coil, for in that case (see Fig. 23, which shows in section a coil of five turns in which the lines of force surrounding one portion of the first turn are depicted), the lines of force surrounding each conductor will evidently, when generated, cut all of the other conductors, and as inductance is manifested only when current strength is changing, this cutting will generate in the portions cut a progressive and continuously opposing E.M.F. If we afford a path of less resistance to the flow of the lines of force than that offered by air, the maximum effect is evidently increased, that is, a given coil has more inductance when a good conductor of magnetic flux, such as iron, wholly or partially encloses the coil. The addition of iron to increase the inductance is, however, not permissible in a standard, for two reasons. First, the permeability of iron is not a constant quantity, but varies with the density of the magnetic induction. Consequently, the inductance, which is proportional to the total magnetic flux divided by the current, is not a constant, but is different for each current strength. This alone would be fatal in a standard, but there is a second property of iron, called "hysteresis," or magnetic retentiveness, owing to which the magnetic flux is not always the same for the same current, but depends, in part, on the preceding magnetic condition of the iron, which furnishes just as potent a reason why the use of iron to increase the inductance of a standard is not permissible.

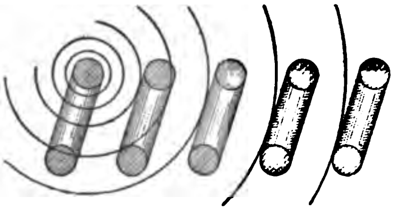

FIG. 23.

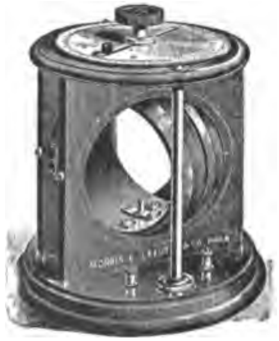

FIG. 24.

If in Fig. 23 instead of having one coil of five turns this were divided into two sections, one of three and the other of two turns, having the relative positions shown, the inductance of the whole would, of course, be the same. If, however, it were arranged so that one of the sections could be displaced relative to the other, the action of one part on the other would be in some manner related to the displacement. This fact is utilized in the inductance standard known as the "Ayrton and Perry," one of which is shown in Fig. 24. This consists of an outer stationary coil of wire within which there is the other coil, and the angle that the latter makes with the axis of the former may be varied by manipulating the knurled button. The inductance is at a maximum when the planes of the two coils are parallel, as then the mutual interaction of the two is greatest; and at a minimum when the planes of the two coils are at right angles, for analogous reasons. A dial-shaped scale is provided over which plays a pointer attached to the axis of the movable element, and by calibration in comparison with other standards the scale may be divided off to show directly the commercial units of inductance (millihenrys) that are offered by each coil position.

CHAPTER III.

GALVANOMETERS.

THE electric current is imponderable and cannot, therefore, be compared as to weight or dimensions with a standard, as ponderable masses are, but must be compared with other currents by means of some effect or property of the current which is a measurable magnitude.

An electric current may manifest itself in several ways. It may effect chemical composition or decomposition, as in the case of the silver voltameter before mentioned; its action may be electromagnetic, in that the magnetic field surrounding the conductor carrying the current will influence an adjacent magnet and tend to displace it, as in an ordinary polarized telegraph relay; its action may be electrostatic, as in the case of pith balls, which are attracted to or repelled from an electrified glass rod; or it may be thermal, as in the case where a current passing through a conductor causes the temperature of the latter to rise.

Instruments for at least detecting the presence and preferably for measuring the magnitude of one or more of these actions are necessary if we are to have a means of comparing current strengths. Such instruments have the generic name of "galvanometers."

Galvanometers based on the chemical action of an electric current are in very limited use and need not be enlarged upon here. The great majority of commercially available forms utilize the electromagnetic manifestations of current and may, generally speaking, be divided into two classes; first, the moving magnet class in which a movable magnet is influenced by the current flowing in a fixed conductor, and the second, the moving coil class, in which the current to be measured, or a known portion thereof, is passed through a movable conductor, usually in the shape of a coil, located within the influence of a magnetic field which may be either that of a permanent magnet, or that of a current-carrying conductor.

In either case one of the elements is fixed and the other free to move against a measurable restraining force, and the extent of the movement of the latter as indicated by suitable means is a measure of current strength. With galvanometers of the first class, those in which there is a movable magnet and a fixed coil, the former is almost invariably a magnetized steel needle or group of needles, usually straight, but sometimes bent double about their centers and taking on the form of a slotted bell (see Fig. 25). In all these instruments the movable needle is suspended from a fiber that offers the minimum possible resistance to its turning, the measurable restraining force being that furnished by an external magnetic field, sometimes that of the earth itself, and sometimes one furnished by adjacent magnets whose positions and distances are adjustable. In high sensibility galvanometers the forces involved are so minute that the delicacy of the suspension becomes a most important item. It is altogether out of the question to use a pointed hardened steel pivot support engaging in a jewel-bearing, as the friction between the two would be commensurate with the deflectional forces and large errors thus introduced. Great delicacy is obtained by supporting the movable needle on a fiber of cocoon silk of considerable length. Even this, however, is inferior to a suspension formed of a very fine filament of quartz. Such may be constructed by heating a short quartz rod to incandescence in an oxyhydrogen blowpipe flame, and having one end rigidly secured to a fixed block, suddenly retracting the other end, usually by having it fastened to a miniature form of crossbow in which, when the trigger is released, the end is shot forward with great velocity. The filament is in this manner drawn out to a very small diameter before rupture.

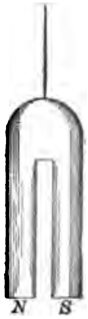

FIG. 25.

As galvanometer sensibility may be increased either by decreasing the amount of restraining force for a given deflectional angle or by increasing the number of ampere turns surrounding the needle, and as the latter is, from motives of efficiency, made as great as possible in the beginning, the sensibility can evidently be further increased only by decreasing the strength of the controlling field. If this is the field due to the earth's magnetism, its directive force may be diminished or, in fact, completely annuled or reversed by placing near to the galvanometer a magnetized body which sets up a flux opposite in direction to that of the earth's field. If the two were exactly alike and opposite there would evidently be no restraining force except the negligible one of the torsional elasticity of the fiber, and the needle, influenced by the current passed through the coil surrounding it, would assume a position practically at right angles to the plane of the coil with any current strength, no matter how small, and thus fail to act as an index of current strength.

When, however, one or the other of the magnetic forces preponderates, there is a directive force which tends to retain the needle in the zero position. The resultant between this and the directive force of the field, due to the flow of the current, determines the position of the needle. Theoretically, therefore, all that is necessary to obtain almost infinite sensibility is an almost infinitesimal difference between the field due to the directive magnet and that of the earth, but this is based on the assumption that the suspension device is frictionless and absolutely flexible. As a matter of fact, the suspension fiber must be of sufficient size to have the necessary strength for the mechanical support of the needle, and the resultant torsional rigidity or inelastic resistance to torsion is of such magnitude that the directive force must be made quite large in order to render it negligible. In practice, to obtain maximum sensibility with a moving magnet galvanometer, a current is passed through it to cause a deflection, preferably the full scale in amplitude, and the current then cut off to see whether the magnet returns to its initial position. If so, the control magnet is approached a little closer. The operation is repeated until, on opening the circuit, the index showing the movement of the needle no longer comes back to its starting point. It is then evident that the controlling force is too weak, so the magnet must be moved away again, just far enough to insure the return of the index to zero every time the current is cut off.

Moving coil instruments may be conveniently divided into two subclasses namely, those in which the coil moves because of the reaction between the current through it and a powerful stationary permanent magnet, and the class in which the reaction is between the current-carrying coil and stationary coils likewise traversed by currents setting up lines of force therein. In movable coil galvanometers, silk and quartz suspension fibers are inadmissible inasmuch as the suspensions are used as a means of conducting the current to be measured to the movable coil. What is ordinarily used, therefore, is a narrow and extremely thin strip of phosphor bronze made by rolling down by successive passages through jeweler's rolls a small diameter phosphor bronze wire. This is, of course, a conductor, and if the movable element be suspended above by one such conductor and steadied below by another, both being held taut, they evidently perform the double function of conductors and opposing springs.

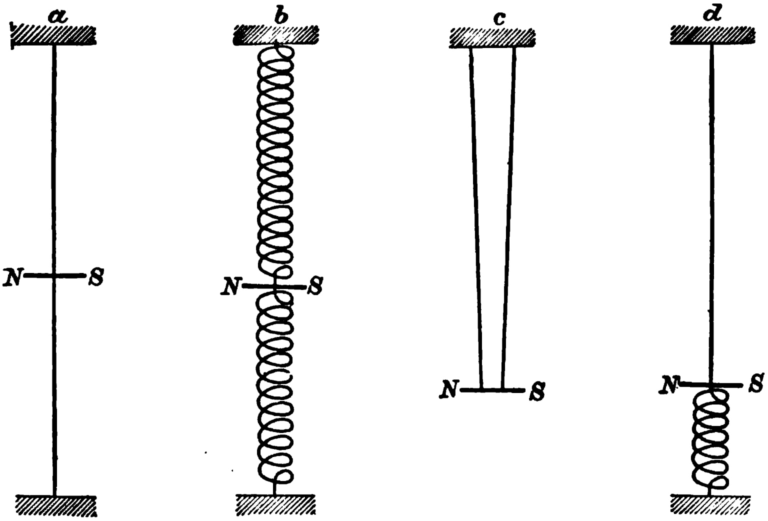

FIG. 26.

It is also possible to support the movable element by two such metallic strips, both supporting it from above. Another form of construction is shown in *b*, Fig. 26. In this construction the metallic strip is coiled helically, and when the movable element deflects, the ordinary spring action of a helically coiled wire is brought into play in place of its torsional elasticity, as in the straight form shown in *a* of the same figure. At *c* is shown the movable coil suspended from above by two conductors, as already mentioned. In the forms *a* and *b* it is evidently possible to substitute for the lower metallic spring strip a very flexible current-carrying strip, which offers no appreciable resistance to motion and at the same time serves as a conductor. Such flexible connections are usually made of soft annealed pure silver wires. In the form of suspension shown in *a*, *b*, and *d*, the resistance to turning offered by the suspensions can be altered only by changing them. In the form shown in *c*, however, if the distance between the two suspensions at their upper end is increased, a greater effort will evidently be required to produce the same angular displacement. This bifilar suspension, as it is called, is convenient in some respects but not in very common use in this country.

The means employed to indicate the extent of the movement of the swinging member of a galvanometer is also of much importance. As the latter usually rotates about an axis, it is evident that any index actuated by it will have a greater linear displacement over a fixed scale for a given angular displacement, the further the scale and the marking extremity of the index are from the axis. This at once suggests the use of a very long hand or pointer, but this is objectionable because of its weight, which not only adds very considerably to the inertia of the moving system, and so renders its response to current changes slow, but necessitates stronger suspensions to support it, which suspensions are, of course, more rigid, and therefore decrease the sensibility of the galvanometer. This difficulty is surmounted by using in place of the ponderable pointer a beam of light reflected from a mirror carried on the movable part. This arrangement may assume one of two forms. In the first, a telescope is used, arranged as shown in Fig. 27, where *ab* is the mirror carried by the moving system, *T* the telescope, and *SS* the scale. The telescope is provided with a stretched hair, *W*, as in a surveyor's transit, which serves as a reference line for the position of the image of the scale markings as seen through the telescope reflected from the mirror. If the moving system, and therefore the mirror, *ab*, attached thereto, moves through an angle α, the angle between the axis of the telescope and the axis of the ray of light reflected from the mirror is evidently 2α, the apparent deflection being thus doubled. In order that there may be a minimum loss in illumination due to the absorption by the lenses in the telescope, the latter is usually made of the astronomical type, presenting to the eye an image that is reversed and inverted (that is to say, turned through an angle of 180°), while the mirror reverses in the sense in which ordinary printing type are reversed. It follows, therefore, that a scale, the reflection of which in a mirror is to be observed, must have its numerals reversed, like ordinary printing type, and if they are to be viewed through an astronomical telescope, the scale must be placed in the instrument in an inverted position, so that the numerals appear to the direct vision thus Ɩ Ƨ Ɛ ᔭ ꙅ. If an erecting telescope or simple slot be used, the scale is placed in the instrument in an erect position, so that the numerals appear to direct vision thus, ϛ ㄣ Ɛ ᄅ Ɩ. In both cases the numerals will appear in their normal aspect, 1 2 3 4 5, when seen while making a scale reading.

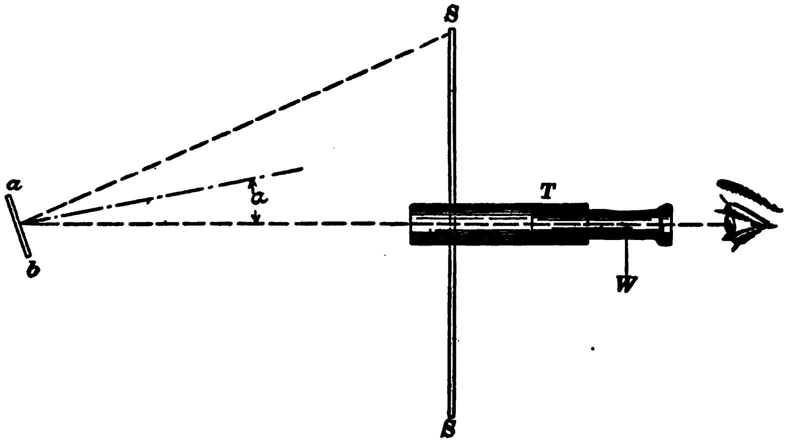

FIG. 27.

On looking through the telescope when current is applied, the whole scale swings across the field or vision, the reference line made by the cross-hair remaining fixed. It is of course possible to use instead of a telescope a small diameter hole or a long narrow slot, but this calls for better illumination, in order to make the scale markings visible, and for good eyesight.

This first type of movement-indicating device enables one to make very close readings, as the cross-hair furnishes a sharply defined reference line. On the other hand, it is trying to the eyes, only one of which can be used at a time. It is also inconvenient in that only one party can observe the indications at a given time.

In the second plan an actual luminous beam is used. Referring to Fig. 28, *L* is a source of light arranged with a hood, or otherwise, so that it sends out only a long narrow beam which is reflected by a mirror or prism at *M*, concentrated by the lens, *l*, and thrown on the galvanometer mirror, *ab*. The latter is made concave to keep the beam concentrated, and the light is thrown from there onto a fixed scale, *SS*, usually made of ground glass and having pasted thereon an opaque scale divided into millimeters, or other convenient units. This beam falling upon the ground glass scale plate makes a luminous line whose position relative to the opaque scale can usually be read with great ease. Readings can be made to a greater degree of accuracy in the telescope pattern instrument because the luminous band has an edge such that it is difficult to say just where it leaves off, but on the other hand, the second form is advantageous because several observers may simultaneously note the swing, and it is much easier on the eyes. The only remaining argument for the first form is that it can be read in the daylight, the brighter the better, whereas the latter needs darkness, if it is to be shown to advantage.

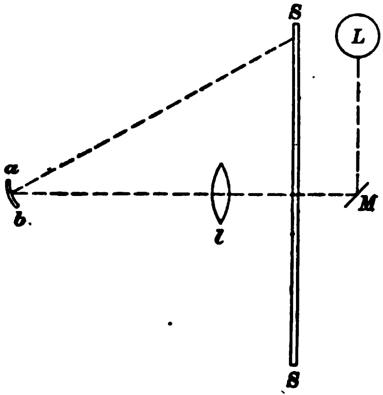

FIG. 28.

Because the scale, *SS*, Figs. 27 and 28, is straight instead of being bent into the form of a circle arc about the mirror as a center, the linear displacements shown thereon are proportionate, not to the angle through which the movable element has swung, but to the tangent of twice that angle. Where the angular deflections are but small, the difference between the numerical value of an angle and its tangent is negligible and the linear displacement on the scale may be taken as proportionate to the angular deflection. However, when measuring large deflections, and where accurate results are required, the angles should be calculated from the above relation between them and the linear motion. The following table computed by Dr. Kennelly gives the correction factors to be applied with different distances between the scale and mirror and for varying deflections:

TABLE II.

Reflecting Galvanometer Scale Errors.

(A. E. KENNELLY.)

(These corrections are to be subtracted from the observed deflections.)

Scale Distance OBSERVED DEFLECTIONS.	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
50	0.05	0.05	0.	0.	0.	0.	0.	0.	0.	0.	0.
60	0.05	0.05	0.05	0.05	0.05	0.	0.	0.	0.	0.	0.
70	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.
80	0.15	0.1	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05
90	0.2	0.15	0.15	0.1	0.1	0.1	0.05	0.05	0.05	0.05	0.05
100	0.25	0.2	0.2	0.15	0.15	0.1	0.1	0.1	0.1	0.05	0.05
110	0.35	0.25	0.25	0.2	0.2	0.15	0.15	0.1	0.1	0.1	0.1
120	0.45	0.35	0.3	0.25	0.25	0.2	0.15	0.15	0.15	0.1	0.1
130	0.55	0.45	0.4	0.3	0.3	0.25	0.2	0.2	0.15	0.15	0.15
140	0.7	0.55	0.5	0.4	0.35	0,3	0.25	0.25	0.2	0.2	0.15
150	0.85	0.7	0.6	0.5	0.4	0.35	0.35	0.3	0.25	0.25	0.2
160	1.0	0.85	0.7	0.6	0.5	0.45	0.4	0.35	0.3	0.3	0.25
170	1.2	1.0	0.85	0.7	0.6	0.55	0.5	0.45	0.4	0.35	0.3
180	1.4	1.2	1.0	0.85	0.7	0.65	0.55	0.5	0.45	0.4	0.35
190	1.65	1.4	1.2	1.0	0.85	0 75	0.65	0.6	0.55	0.5	0.45
200	1.95	1.65	1 4	1.15	1.0	0.9	0.8	0.7	0.6	0.55	0.5
210	2.25	1.9	1.6	1.35	1.15	1.05	0.9	0.8	0.7	0.65	0.6
220	2.6	2.15	1.8	1,55	1.3	1.2	1.05	0.9	0.8	0.75	0.65
230	2.95	2.45	2.05	1.75	1.5	1.35	1 2	1.05	0.95	0.85	0.75
240	3.3	2.8	2.35	2.0	1.75	1.5	1.35	1.2	1.05	0.95	0.85
250	3.75	3.15	2.65	2.25	1 95	1.7	1.5	1.35	1.2	1.05	1.0
260	4.25	3.5	3.0	2.55	2.2	1.9	1.7	1.5	1.35	1.2	1.10
270	4.75	3.95	3.35	2.85	2.45	2.15	1.9	1.7	1.5	1.35	1.25
280	5.3	4.4	3.7	3.15	2.75	2.4	2.1	1.9	1.65	1.5	1.35
290	5.85	4.85	4.1	3.5	3.05	2.65	2.35	2.1	1.85	1.65	1.5
300	6.45	5.35	4.5	3.9	3.35	2.95	2.6	2.3	2.05	1.85	1.7
310	7.1	5.9	5.0	4.3	3.7	3.25	2.85	2.5	2.25	2.05	1.85
320	7.8	6.5	5.5	4.7	4.05	3.55	3.15	2.75	2.45	2.25	2.05
330	8.5	7.1	6.0	5.15	4.45	3.9	3.45	3.05	2.7	2.45	2.2
340	9.3	7.75	6.55	5.6	4.85	4.25	3.75	3.35	2.95	2.65	2.4
350	10.1	8.4	7.15	6.1	5.3	4.6	4.1	3.65	3.25	2.9	2.6
360	10.95	9.15	7.75	6.65	5.75	5.0	4.45	3.95	3.55	3.15	2.85
370	11.85	9.9	8.4	7.2	6.2	5.45	4.8	4.3	3.85	3.40	3.1
380	12.8	10.7	9.05	7.8	6.7	5.9	5.2	4.65	4.15	3.7	3.85
390	13.8	11.5	9.75	8.4	7.25	6.35	5.6	5.0	4.45	4.0	3.6
400	14.85	12.4	10.5	9.05	7.85	6.85	6.05	5.35	4.80	4.3	3.9
410	15.9	13.3	11.3	9.7	8.4	7.4	6.5	5.75	5.2	4.65	4.2
420	17.05	14.25	12.1	10.4	9.05	7.95	7.0	6.2	5.55	5.0	4.5
430	18.2	15.25	12 95	11.15	9.7	8.5	7 5	6.65	5.95	5.35	4.85
440	19.45	16.3	13.85	11 9	10.35	9.05	8.0	7.1	6.35	5.75	5.2
450	20.7	17.35	14.75	12.7	11.05	9.7	8.55	7.6	6.8	6.15	5.55
460	22.05	18.5	15.75	13.5	11.8	10.35	9.1	8.1	7.25	6.55	5.9
470	23.45	19.65	16.8	14.4	12.55	11.0	9.7	8.65	7.75	6.95	6.3
480	24 85	20.9	17.85	15 3	13.3	11.7	10.35	9.2	8.25	7.4	6.7
490	26.35	22.2	18.9	16.25	14.15	12.4	11 0	9.75	8.75	7.85	7.1
500	27.9	23.55	19.95	17.2	15.0	13.2	11.65	10.35	9.3	8.35	7.55

We will now proceed to consider commercial forms of galvanometers.

MOVABLE COIL OR D'ARSONVAL TYPE.

Galvanometers with movable coils through which the current to be measured is passed, and in which the coils rotate in the field furnished by a powerful permanent magnet, are said to be of the D'Arsonval type. An early form of the D'Arsonval galvanometer is shown in Fig. 29. The magnet furnishing the field is of the compound pattern made of several U-shaped permanent magnets bolted together and secured vertically to the base of the apparatus. In the gap between the legs of the magnet is placed a cylinder of soft iron supported from the rear, which decreases the reluctance of the magnetic circuit and makes the density in the air gap between its face and the magnet faces a maximum, the resultant powerful field giving a maximum reaction for a given current strength. Surrounding the central

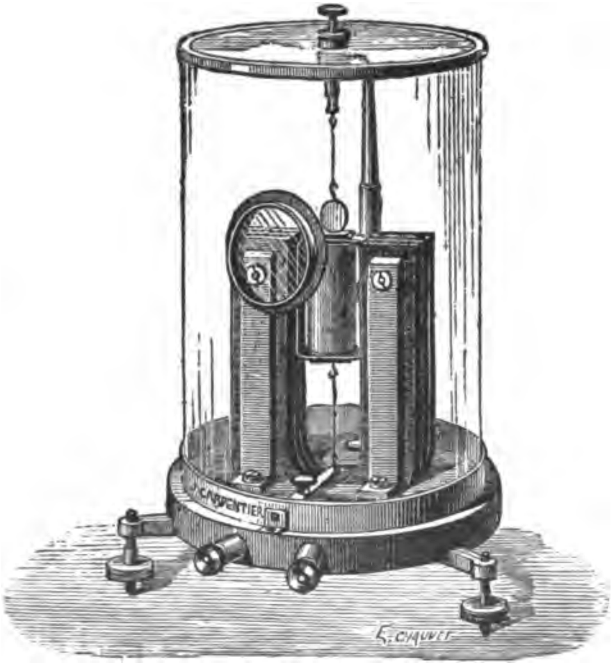

FIG. 29.

cylindrical core, there is a rectangular loop made of many turns of wire supported from above, coaxially with the cylinder by means of a fine silver or alloy strip, as already mentioned. The lower side of the loop is steadied by a similar strip, which in turn is secured at its end to a stiff flat brass spring. The elasticity of this spring keeps the strips taut and the coil perfectly centered. The tension on the strips may be varied by means of a suitable thumb-screw, as shown. A small circular mirror having either a plane or a concave surface, according to the method to be employed in reading the indications of the instrument, is cemented to an upright rod firmly attached to the coil. The current to be measured is led into the coil through the upper metallic suspension, through the several turns of wire composing the coil, and out again through the lower strip and flat spring attached thereto. The whole apparatus is kept covered by a glass bell to prevent disturbance by air currents, and in the bell jar there is provided, a window of very thin clear glass, such as used for microscope slides, through which the beam of light may pass without distortion.

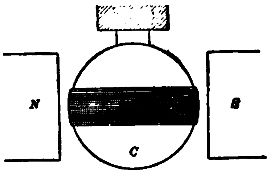

FIG. 30.

It will be observed (see Fig. 30 showing diagrammatically a plan view of a suspended coil galvanometer) that the D'Arsonval instrument is simply a miniature motor, with fixed permanent magnets for furnishing the field flux, the movable coil, *e*, forming the armature winding, and the fixed cylinder, *c*, the armature core. The force with which the coil tends to place itself at right angles to the position shown is thus dependent upon exactly the same elements that determine the torque of a motor, that is to say, the strength of the field, the number of turns of wire in the coil, and the strength of the current flowing through that coil. High sensibility may therefore be obtained by using the most powerful possible permanent magnets, and by the employment of the maximum number of turns of fine insulated wire in the loop, at the same time making the restraining force of the elastic strips as small as possible. If instead of simply winding the wire into a rectangular coil, it is wound up on a metallic frame, preferably copper or aluminum, because of the good conducting quality of these metals, weight considered, the indications of the instrument become "dead-beat," that is, when current is applied, the coil swings at once to the position corresponding to the current strength without oscillation around it. When the coil swings, the metallic frame acts like a short-circuited conductor in a motor armature; the currents circulating therein require energy for their generation, and that energy is deducted from the momentum of the moving parts, causing them to come to rest almost instantly.

In the original form of D'Arsonval galvanometer just described, the field is not uniform, as the air gap between the cylindrical core and the plane faces of the magnet is, of course, of different depth at different points. As the torsional reaction of the suspension fibers increases in direct proportion to the angle of twist, deflections that are directly proportional to the current strength are obtained only when the coil revolves in a uniform magnetic field. A uniform field may be obtained by shaping the poles of the magnet, so that they embrace the central core and leave a uniform air gap, or the same end may be attained by attaching to the magnet poles, iron extension pieces similarly shaped. It is convenient to have an instrument in which the angular deflections are in direct proportion to the current strength, as this greatly facilitates the comparison of different currents with one another.

It is claimed by some authorities that the most efficient form of the moving coil is a shuttle shape without a central core, instead of the rectangular one employing a core. A modern galvanometer in which this construction is employed is shown in Fig. 31. It will be noted that here the magnet is placed horizontally, instead of vertically, and composed of a large number of comparatively thin separate magnets stacked one on top of another. Instead of shielding the whole instrument by a glass bell jar, the revolving coil, suspension, and mirror are enclosed in a brass tube, a small glass window being provided opposite the mirror, through

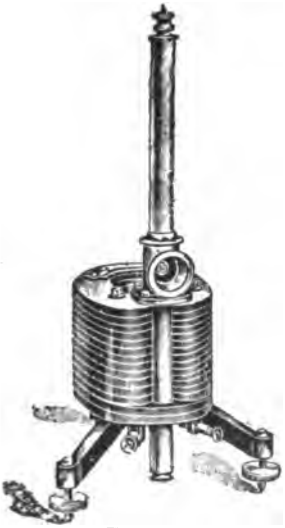

FIG. 31.

which the beam of light indicating the extent of motion may pass. The complete brass tube with its contents may be removed from the magnetic structure without disturbing any connection, as contacts are made with the coil through stationary spring plates in electrical contact with the terminal binding posts.

Instruments so built may be made of very high sensibility, for instance, one having a resistance of about 200 ohms may be able to show a deflection of the beam of light thrown from a fixed source to the mirror carried by the moving system, and back again to a fixed translucent scale placed 1 meter away from the instrument, of 1 millimeter when 200 megohms are placed in series with the galvanometer, and a potential of 1 volt applied to the free galvanometer and resistance terminals respectively. With a coil having a resistance of about 3,500 ohms 1 millimeter deflection can be had through about 1,500 megohms with 1 volt.

It must be confessed that these stated sensibilities are somewhat misleading, as they are due in part to using a suspension fiber that is so delicate that elastic fatigue will often become noticeable. With such high sensibility instruments it is by no means uncommon to have the light spot on the scale refuse to return to the zero mark after current is cut off, at least until the lapse of a period that may be reckoned in hours, and sometimes even days. The low mechanical strength of the suspensions introduces another objectionable feature, their great liability to rupture. Means are usually provided for removing the strain on the suspension and then firmly clamping the coil when the instrument is to be transported, but the suspensions are nevertheless frequently broken after the galvanometers are set up, and their replacement is then tedious work. Not only is time required for the delicate operation of replacing the broken suspension, but the calibration, namely, the deflection, given by a stated current must be determined afresh. This is different for different suspensions, not so much because these vary in resistance, for their resistance is generally negligible as compared with that of the coil and the external circuit, but because of the different torsional rigidity of different specimens. As the latter are commonly made by flattening a wire of a diameter of about .002 inches in a set of jeweler's rolls, it is practically impossible to get the resulting strips of uniform size and uniform elasticity.

One other objection to this sensitive form of D'Arsonval galvanometer is the fact that the mechanical clearance between the coil and the magnet face is reduced to a minimum in order to reduce the length of the air gap in the magnetic circuit and therefore increase the density of the lines of force flowing therethrough. Because of this small clearance it becomes necessary to level the instrument with exceeding care so that the coil may not touch the poles at any point. On the other hand, they are valuable in workshops and laboratories, because they combine with high sensibility immunity from disturbance by stray magnetic fields, as the one in which the coil swings is so very strong as to mask any others that are apt to exist at the point of use.

A form of D'Arsonval galvanometer that is almost entirely free from the objections to which the sensitive form is open, but which, on the other hand, is of lesser sensibility, is illustrated in Fig. 32. This Chauvin and Arnoux instrument is like the original D'Arsonval pattern, in that a central stationary core is used. The coil consists of a rectangular copper frame around which is wound the moving wire. It does not require the special leveling screws employed in the high sensitive form, as it is provided with a gimbal interposed between the instrument proper and the wall-plate, which device of course makes the instrument hang perfectly vertical if the plate is screwed upon the wall. The suspension for the coil also differs from those in the high sensibility devices; it is formed, not of a straight thin strip of bronze, but a strip of very elastic high conductivity alloy wound helically about a mandrel that is about as big as a knitting needle. The toughness of these suspensions is almost incredible, being such that the makers find it entirely superfluous to supply any means of blocking the coil while in transit. They can be shipped around by express, and the writer has even known of one being thrown to the ground with such violence that the mirror became dislodged without causing the suspension to break or to be deformed sufficiently to prevent the coil from swinging freely in its allotted position when the instrument was again hung up. This same suspension is of advantage where mechanical vibration exists at the point of installation, as it serves to cushion that vibration and greatly diminishes the dancing about of the light spot that is so objectionable in the high sensibility form and frequently renders it impossible to take any readings whatsoever. In the Chauvin and Arnoux instrument the support for the scale is arranged to be carried by the instrument itself, and the telescope method (see page 43) of making readings is employed in order to render unnecessary the employment of a source of artificial light. It is very light and so small that when

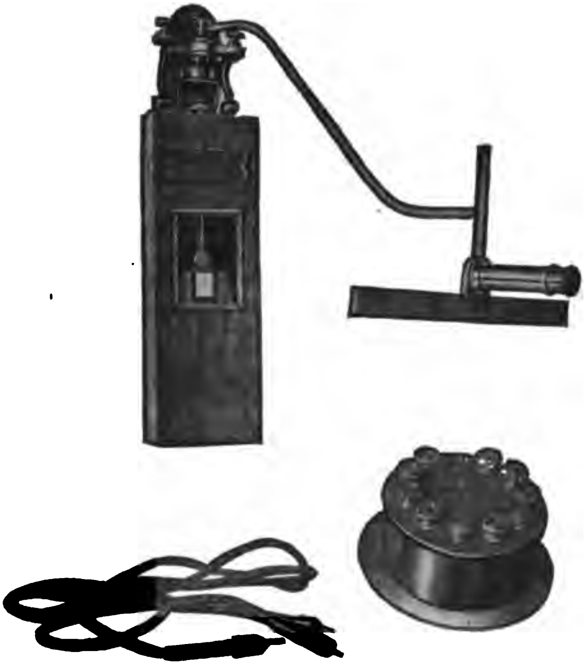

FIG. 32.

the scale support and scale is removed it may be carried in a coat pocket. With 1 meter distance between the mirror and the scale an instrument having a resistance of about 175 ohms will give a deflection of somewhat over 1 millimeter with 1 volt when about 90 megohms are inserted in series. Comparing this with the high sensibility form, it will be seen that the sensibility of the Chauvin and Arnoux pattern is less than one half as great.

In the D'Arsonval instruments mentioned above, the force that opposes the motion of the coil is that offered by a strip of elastic metal which is being put under torsion. An interesting variation is where the elasticity of the suspension is made as small as possible and the opposing force supplied by magnetic attraction. Referring to Fig. 33, if the filaments attached to the moving coil are conductors, but so flexible that they offer practically no resistance to the rotation of the coil, any current that may be passed would cause the coil to move and assume a position where its plane is at right angles to the direction of the lines of force in the field between the two magnetic poles. If, however, the wire forming the coil is, as was suggested many years ago (British patent, No. 8,795, of 1887, to Ayrton and Perry), of iron, or is wound on rectangular iron form, the magnetic flux between the poles will tend to hold the coil so that its plane is parallel to the direction of the lines of force, and the further the plane of the coil departs from this position by rotating around the axis formed by suspension fiber, the greater is the force tending to bring it back again. We therefore have the opposing force furnished by a body that is influenced by the same magnetic force whose reaction with the current causes the coil to move. This tends to preserve stability of calibration, for if the strength of the fixed magnet decreases, the reaction between it and a given current in the coil decreases, but the force opposing the coil motion likewise diminishes as the effort to hold the iron ele-

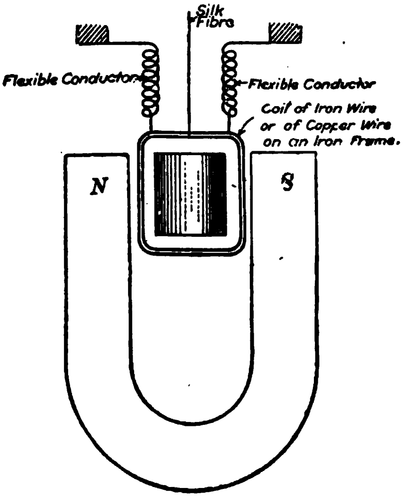

FIG. 33.

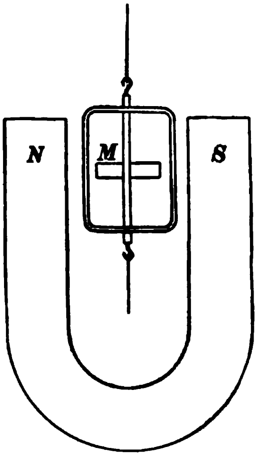

FIG. 34.

ment in line is no longer as great. This form of galvanometer has been reinvented of late by Mr. Weiss, and was described by him in a communication to the French Academy of Science in the early part of 1902. Fig. 34 shows the instrument. The iron element here takes the form of a short bar, *M*. It is claimed that the strength of the magnet may vary as much as 20 per cent without changing the calibration. Pivot-borne instruments of this class, for commercial measurements of current and voltage, have likewise recently been placed on the market in this country.

REFLECTING ELECTRO-DYNAMOMETERS.

The preceding instruments are suitable only for the measurement of direct currents, because the field furnished by the permanent magnet is constant in direction, so that if the current passed through the movable coil be reversed, the deflecting force is reversed also. The inertia of the coil will not allow it to follow these reversals, so the only effect, if an alternating current is applied, will be a slight trembling of the mirror and the beam of light reflected therefrom. A moving coil galvanometer, which responds to either direct or alternating current, is called an electro-dynamometer, an example of which, well known in this country, is the form designed by the late Professor Rowland. In it the field in which the moving coil swings is supplied by a stationary coil of wire. Through this coil is passed current derived from the same source as that flowing through the movable coil. In this apparatus, even if the current be constantly changing in direction, that in the fixed and movable coils is simultaneously reversed, the resultant, therefore, being a constant effort to turn the coil in one direction. As is shown in the diagrammatic illustration in Fig. 35, there are two fixed coils, one of fine wire of many turns, and the other of coarse wire of few turns, these being introduced in order to extend the range of the instrument and make its capacity suited to the measurement of both large and small currents. Separate terminals are provided for each winding so that they may be interconnected in any way desired. It is not feasible to make the indications of this class of galvanometers "dead beat" by winding the movable coil on a metallic frame, for if this were done currents would be induced in that frame when alternating currents passed through the fixed coil, and the repulsion between these currents would cause a deflection, even if no external current at all were applied to the moving one. The oscillations are therefore damped by mechanical means, a vane of mica being secured to the moving coil and fitted closely in a stationary air-tight box. The sensibility of these instruments is by no means as great as galvanometers of the D'Arsonval type, as the magnetic field furnished by the fixed coils is of far less intensity. It is, however, sufficiently great so that an alternating current of .0001 ampere, or an alternating potential of .005 volt may be measured. The sensibility for direct current is somewhat higher, but many precautions must be observed in direct current measurements with reflecting electro-dynamometers, in order to eliminate the influence of foreign magnetic fields, notably the earth's field as modified by magnetic bodies in the vicinity of the apparatus. A complete Rowland electro-dynamometer is illustrated in Fig. 36. It will be noted that deflections of the moving part are observed with the aid of a telescope and fixed scale, as described on page 44.

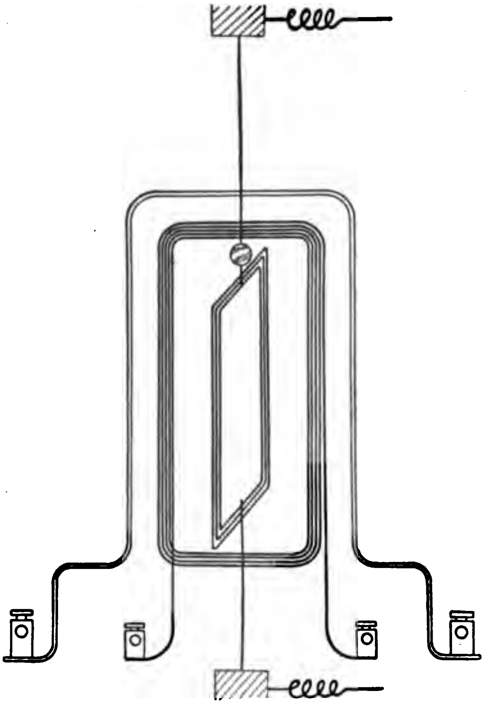
FIG. 35.

MOVING MAGNET GALVANOMETERS.

Galvanometers in which the magnet moved and the coil conveying the current to be measured was held stationary, formed the earliest type of these instruments. In their elementary form such galvanometers consisted of a compass needle supported on a pivot, which was deflected by current passed, parallel to its length, over and under several times, through a coil of wire. The natural evolution of this form led to an instrument in which the needle was suspended by a fine silken fiber which introduced a far smaller error due to torsional rigidity in the fiber than was introduced by the friction between the pivot and the jewel resting thereon. Of course, the deflection caused by a given current is increased in proportion to the number of times that the current acts on the needle, in other words, by having an increased number of turns in the coil surrounding it.

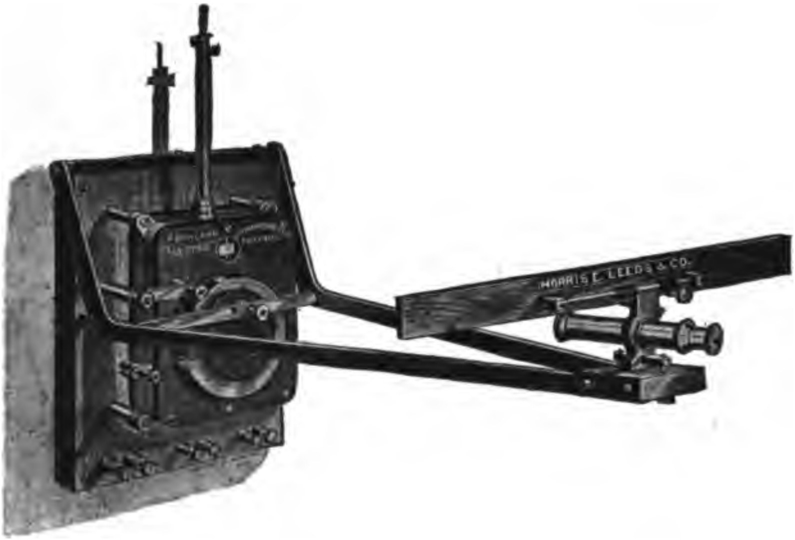

FIG. 36.

This expedient cannot be carried too far, however, as increased turns mean an increased length of wire, and hence resistance for the current to overcome, and the last turns are necessarily further removed from the needle than the earlier ones, and hence of less efficiency. The next step to increase sensibility is to decrease the directive force tending to hold the needle in a given position. If, as is usually the case, the directive force is that due to the earth's field, its intensity may be diminished by placing a permanent magnet near the apparatus, in such a position that the field surrounding it is opposite to the earth's field. The magnet is, of course, not adjusted, so that its field and the earth's field entirely neutralize one another, as this means no directive force whatsoever. It can, however, be adjusted so that one or the other preponderates but slightly, and the sensibility of the apparatus is correspondingly increased. At this point it might be noted that it is possible to make the movable element of a moving magnet galvanometer of a weight the fraction of that of the coil in the D'Arsonval type, and hence far finer suspensions are permissible, with a resulting decrease of the force necessary to twist them through a given angle and a corresponding increase of sensibility. As it is not necessary to convey currents to and from the movable element through the suspensions, only one need be used, and that may be of nonconducting material. These features contribute to high sensibility.

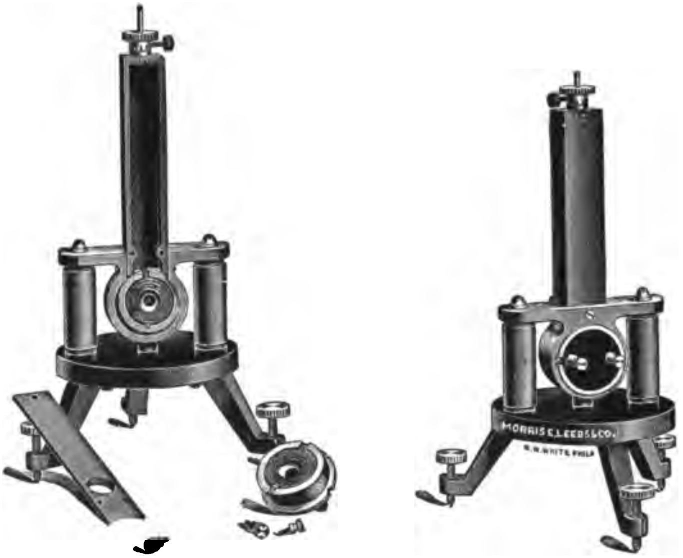

FIG. 37.

A prominent moving magnet galvanometer of the above described type is the "Kelvin instrument," illustrated in Fig. 37. The magnet here takes the form shown in Fig. 38, where three short pieces of watch spring are flattened out and cemented to a mica disk supported by a quartz or silk fiber. This construction is very light and compact. In the Kelvin instrument, the current-carrying coil is divided up into two halves, one of which is movable, so that access may be had to the magnet system, and the suspension renewed, if broken. The magnet for varying the sensibility, by neutralizing, the earth's field to a greater or less degree, is not shown in Fig. 37. It is arranged below the apparatus and equipped with a slow-motion screw, so that a fine adjustment of the position of the directive magnet relative to the moving needle is possible.

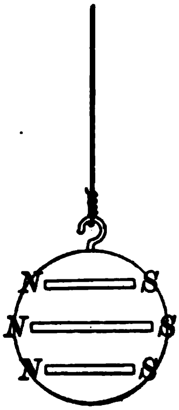

FIG. 38.

This particular class of Kelvin instrument is objectionable because of its extreme sensibility to disturbances due to stray magnetic fields. If the control magnet is adjusted almost to neutralize the controlling effect of the earth's field, any minute variation of the latter due to the presence of magnetic bodies will cause the needle to deflect; the same effect being, of course, caused by neighboring current-carrying conductors which set up fields modifying the influence of the earth's field. This sensibility to magnetic disturbances may be partially overcome as follows: Referring to Fig. 39, if two magnetized needles of like strength are rigidly coupled together with their ends of the same magnetic polarity pointing in opposite directions, the tendency of the earth's field to keep one needle in a given position is evidently opposite to and neutralized by its tendency to keep the other needle in just the reverse position. Such a magnetized pair will therefore take up any position freely when in a field as nearly uniform as that of the earth, and is said to be "astatic." An astatic couple for a Kelvin instrument is formed by rigidly joining together in a similar way two of the sets of magnetized watch springs cemented to mica disks used in the plain instrument just described. Both the upper and lower elements are surrounded by wire coils interconnected so that the sum of all the efforts is to cause the element to rotate in a given direction. Each of the two coils is wound in two sections, as in the case of the simpler instruments, and one pair of these is likewise movable, in order that access may be had to the moving part. Fig. 40 shows a four-coil Kelvin

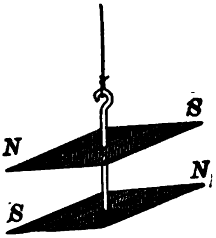

FIG. 39.

galvanometer, the second illustration showing the front coils swung down out of the way and the tube carrying the magnets swung out from the rear coils in order that free access may be had all around it. The mirror, as will be noted, is fastened to the rod joining the two magnetic elements, midway between them. The other cut in Fig. 40 shows the instrument assembled and the directive magnet below it. This magnet is closer to the lower set of needles than the upper one, and hence, influences the latter more and furnishes a directive force sufficient to hold it in a given position. The four coils may, of course, be coupled together in series or parallel as desired, or in opposition, namely, differentially, so that the deflection due to the difference between the strength of two currents may be observed.

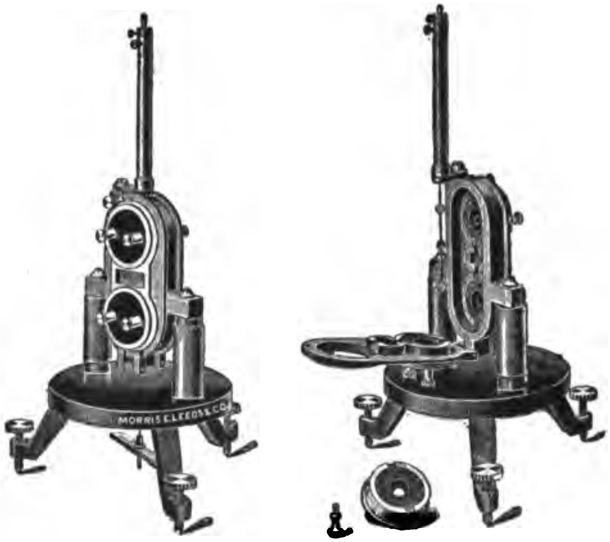
MORRIS E. LEEDS & CO.

FIG 40.

The construction of these instruments is not such that the indications are inherently "dead beat," and it is necessary to apply extraneous methods of damping if rapid readings are to be taken. In some forms this is accomplished by attaching to the moving system a thin vane immersed in oil, but it is more common to make the mica disks on which the magnetized watch springs are cemented fit rather closely in a spherical chamber so that the indications are air dampened. If the hollow chamber has massive copper walls, this also damps the oscillations, as the moving magnet expends energy in setting up currents in the copper and there is, hence, less force available to move it beyond the position corresponding to the current strength.

The four-coil Kelvin galvanometer, notwithstanding the fact that it is provided with an astatic pair of needles, is by no means entirely immune from disturbances by external magnetic forces. This is because it is seldom that such forces are sensibly the same in the regions of both magnets; or, in other words, that such external fields of force are uniform.

It is also exceedingly susceptible to mechanical vibrations and must be mounted with extreme care in order that such vibrations may not affect it sufficiently to throw the light spot off the scale. On the other hand these galvanometers have the highest sensibility attainable.

HOT WIRE GALVANOMETERS.

When an electric current flows through a conductor, a resistance to that flow is encountered, and the work done by the current in overcoming the resistance heats the conductor. If the conductor is a fine wire and the current is comparatively heavy, the resultant expansion, suitably multiplied and indicated, may be used to measure the current strength. The use of galvanometers utilizing this principle is not general, because their sensibility is not high; they are sluggish in their indications, owing to the time required for the wire to attain its new temperature when the current strength changes, and it is difficult to compensate for changes in the temperature of the air surrounding them and to shield the wire from slight air currents.

On the other hand, they have the great advantage for alternating current measurements, that their self-induction and capacity is practically zero, and hence their use does not alter circuit conditions.

One of the most sensitive instruments of this class consists of two very fine wires of manganin or platinum silver alloy stretched parallel to one another a short distance apart, their ends being secured to appropriate abutments. These wires are embraced at the center by a very small loop of stiff paper carrying a small plane mirror. A microscopic hook at the end of a fine light spring is slipped over one of the wires near the paper loop, the mirror in this way being pulled around to a certain angle about the other wire as a center. When current flows through the wire on which this hook is caught, the expansion of the wire due to its heating allows the spring to pull the mirror over still further, the resultant deflection being read off on a suitable scale by the conventional spot of light. For maximum sensibility to small currents, the wires are made of a material having as high a specific resistance as can be obtained in order to make the heating effect, which, with a given current, varies as the resistance, a maximum. To get the greatest deflection with a low voltage the wires are made of as low resistance as is feasible, in order that a maximum current strength may flow and hence cause maximum elongation.

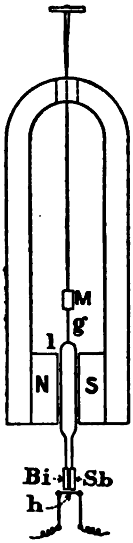

FIG. 40 *A*.

Several galvanometers working on this principle have been brought out from time to time, notably those of Prof. Threlfall and of Dr. Fleming. In this country, a similar instrument is made by Leeds and Northrup.

RADIATION GALVANOMETERS.

The most sensitive galvanometers for the detection of alternating currents seem to be those in which the heating of a wire carrying current is indicated, not by a magnification of the change in length of the wire, but by radiation of its heat to a delicate thermo-couple. The Duddell instrument, made on this principle, is diagrammatically illustrated in Fig. 40 *A*. As will be seen from this, a loop consisting of a single turn of wire is placed in the field of a magnet like that in the conventional D'Arsonval galvanometer. The two ends of the loop terminate in a thermo-couple, which is placed close to the short straight wire through which the current to be measured is led. The heat radiated from the wire causes a current to flow from the thermo-couple through the loop, and that current brings about a deflection of the loop in the conventional manner. The deflections are read off by the aid of the mirror, *M*, in the ordinary way. According to Duddell, such a galvanometer will show an apparent scale deflection of 2 millimeters with 1 millivolt difference of potential, at the resistance wire ends. The currents generated by talking into a Bell telephone receiver are sufficient to throw the beam of light entirely off the scale. An instrument having a resistance of 18 ohms is capable of measuring a current as low as 160 micro-amperes.

REFLECTING ELECTROMETERS.

The electrostatic instrument shown in its elementary form in Fig. 19 and described on page 30, may, when suitably designed and provided with a long, delicate suspension and a mirror for taking readings, be made a galvanometer of value for certain alternating and direct current measurements. Its sensibility is by no means as high as that of a very ordinary direct current galvanometer or of the galvanometer responsive to both direct and alternating currents just described, but it has the advantage of possessing a practically infinite resistance, no inductance and small capacity. The first of these characteristics is of peculiar advantage in certain direct as well as alternating current measments as the electromotive force measured by the twisting of the suspension as shown by the deflection of the beam of light from its mirror is that of the source under test when it is supplying no current, that is to say, it is the *open circuit E.M.F.*, a value that often requires determintion.

In using electrostatic galvanometers, there is a source of possible error which must always be considered. The suspension fiber supporting the movable vane in such instruments must necessarily be a conductor of electricity in order that the current required to charge the vane may be conveyed to it. The fiber and the vane are almost invariably of different chemical composition, usually phosphor bronze and aluminum respectively, and when two dissimilar metals are placed in contact it is well known that there will exist a difference of potential, usually called a "Contact E.M.F." between them. The movable element thus always has a small initial charge, and if it is further charged by applying current to the apparatus in such a direction that the new charge assists the initial one, the deflection will be greater, by twice that due to the initial charge, than if the potential of the circuit to be measured were applied in the opposite direction. If the instrument is always to be used with direct current, and care is taken to see that the same pole of the applied circuit is always attached to a given binding post, this error may be allowed for in the calibration. If alternating current be measured, however, a correction equal to the initial charge must be applied. A reflecting electrometer is shown in Fig. 41.

For the very highest sensibilities the suspension for the moving element of an electrometer may be made of a quartz fiber on which is chemically precipitated a very thin, adherent film of gold to render it conducting. With a suspension of this sort a sensibility may be obtained such that it is possible to get a deflection of 200 or more millimeters on a scale placed 1 meter away from the mirror with 1 volt. As the deflections of electrostatic instruments increase as the square of the applied voltage, a very high deflection for a given E.M.F. may evidently be obtained by applying a steady initial E.M.F. of some magnitude and then superimposing the unknown one on that. In this way the sensibility of a reflecting electrometer may be increased enormously.

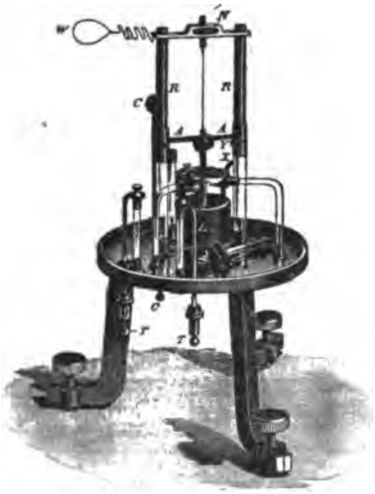

FIG. 41.

THE TELEPHONE RECEIVER.

The conventional telephone receiver is a convenient and simple piece of apparatus often used for the detection of feeble electric currents.

Of course, it cannot of itself measure current strength as its indications are audible only, and the human ear cannot evaluate tone volume with any accuracy, but it does form a sensitive means for showing whether a difference of potential does or does not exist. It is naturally necessary to arrange the apparatus so that the circuit through the receiver may be successively made and broken, because it is only on the make and on the break that the diaphragm of the receiver will respond and give forth a clicking sound.

A good telephone receiver having a resistance of about 100 ohms will give an audible click when a circuit passing .005 milliamperes through it is made or broken.

The advantages of a telephone receiver for this kind of work are its low cost, its portability, the fact that it need not be leveled or placed in any definite position, and that it is not affected by stray magnetic fields.

CAPILLARY ELECTROMETERS.

An effective device for detecting and measuring very small direct current E.M.F.'s is made by enclosing in a glass tube of very fine bore, clean, pure mercury and a strong solution of sulphuric acid, the two being in contact with one another. When a potential difference is applied between the two ends of the tube, an action takes place at the surface of contact between the mercury and the acid which causes a change in the capillary pressure. This in turn causes a displacement of the surface of the mercury which, while small, may easily be read with the aid of a microscope. For small differences of potential the displacement is directly proportionate to the potential.

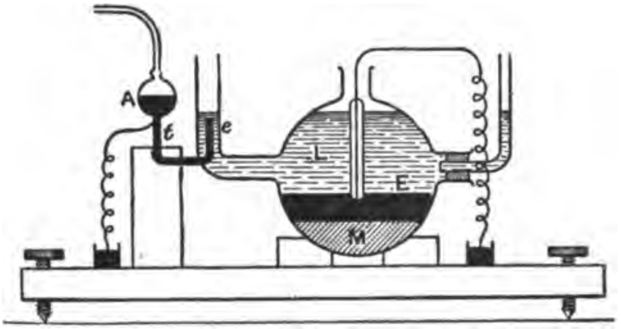

FIG. 42.

Obviously, a device built on the above principle may assume many forms. In Fig. 42 is shown the Boley type, in which the mercury is contained in a spherical glass chamber *A* which communicates with the acid solution at *e* through the fine bore tube *t*. A relatively large volume of the electrolyte *L* is provided in order to have a large contact area available between it and the other mercury electrode *E* through which current is introduced, this large area being desirable to prevent rapid polarization. The level at which the mercury in the fine bore tube *t* comes in contact with the electrolyte can obviously be adjusted by varying the air pressure on the surface of the mercury in *A* or by varying the depth of the electrolyte in its chambers.

The change in level caused by the application of an E.M.F. to the instrument is observed through a microscope, an apparent change of 1 millimeter being shown, with a magnifying power of 100, with a potential change of .0024 volts. The instrument can be read to .0002 volts without difficulty and it is claimed that the changes in level are exactly proportionate to the voltage up to .01 volts.

Capillary electrometers are not in common use as they have unstable zeros, are not portable, and the microscope method of taking readings is very hard on the eyes.

GALVANOMETER SHUNTS.

Plain Shunts.

A commercial galvanometer is naturally made of the highest sensibility consistent with its cost and type in order that it may be suitable for delicate and accurate work.

For preliminary measurements, the sensibility of an average galvanometer is often too high, however, and in making the first adjustments, currents may flow that will either burn out the windings or injure the device mechanically by deflecting the moving portion too violently against the stops provided to limit the motion. An arrangement of several galvanometers of varying sensibility to be used successively would evidently be both awkward and costly. Devices are therefore supplied, by the aid of which the sensibility of a given galvanometer may be varied from its maximum by successive steps to any desired minimum, and these devices are called "galvanometer shunts."

Referring to Fig. 43, let *G* represent a galvanometer of resistance *G*, *B* the source of the current to be measured, and *x* a resistance which may be inserted between the galvanometer terminals. From the law of divided circuits (see page 93), the resistance of the circuit formed by the galvanometer and the shunt x connected to its terminals is $\frac{Gx}{G+x}$ and, if the current flowing through the battery circuit is A amperes, the fraction thereof that flows through the galvanometer is $\frac{Ax}{G+x}$. To take a concrete case, if G is 900 ohms, and x is made 100 ohms, $\frac{100}{900+100} = .1$ of the battery current goes through the galvanometer and the same current from the battery that would cause a given deflection with no galvanometer shunt will cause but one tenth of that deflection with the shunt attached, provided, of course, that the galvanometer is of a pattern in which the deflections are proportionate to the current. It is usual to supply a set of shunt resistances like x in the figure, all built into one case and having suitable binding-posts for the attachment of the various wires. Such shunts are usually made $\frac{1}{9}$, $\frac{1}{99}$, and $\frac{1}{999}$ of the galvanometer resistance, reducing the sensibility to respectively .1, and .01, and .001 of the normal. One of them is illustrated in Fig. 44. In order to have the simple decimal relationship between the value of the deflections when such shunts are used, it is evidently necessary to have the shunt resistances accurately adjusted to work with the given galvanometer. A separate shunt-box is therefore required for each instrument.

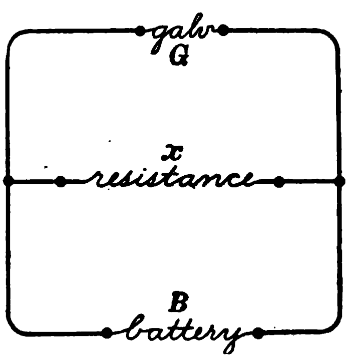

FIG. 43.

Compensated Shunts.

It will be noticed that with simple shunts of the character just described, the combined resistance of the galvanometer and shunt will vary with the shunts of different values. This is a feature that is often objectionable, because with a given source of E.M.F. the current through the galvanometer circuit will vary with every step. It is therefore evident, if we have a given E.M.F. which produced a given deflection with the one tenth shunt in, this deflection is not one tenth of that which would have been given with the same E.M.F. and no shunt, but differs by an amount dependent on the resistance of both shunt and galvanometer. To correct this, compensated shunt-boxes are made, in which, when the movable plug is shifted to insert any ratio shunt, there is inserted at the same time an auxiliary resistance in the galvanometer circuit, which offsets the changed resistance of the whole, and keeps the effective resistance between the battery terminals constant. The way in which this is done can be seen from inspection of Fig. 45. Owing to the greater amount of work involved in adjustment, these compensated shunts are far more costly than the type described before, and consequently are in less common use.

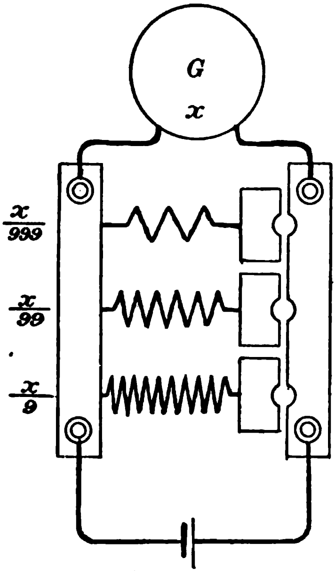

FIG. 44.

The Ayrton Shunt.

As above stated, galvanometer shunts of the types just described are open to the objection that each must be separately adjusted to work with the galvanometer with which it is to be used. This is a disadvantage not only in that it necessitates the purchase of as many shunts as the user has instruments, but because if a galvanometer should be injured and require rewinding, its shunt would have to be readjusted too, thus adding considerably to the expense. Such shunts are also objectionable in that, while correct for a steady current, the indications of the galvanometer with which they are used are not correct when measuring current impulses that exist only momentarily, as in measuring capacity. The proof of this need not be given here, although it may be of interest to note that the tendency is to make the galvanometer read too low.

The universal shunt devised by Ayrton and Mather escapes these objections. This shunt is universal in that it need not be adjusted to any particular galvaonmeter but can be used interchangeably with all, and the results are accurate whether the current flow is continuous or only momentary. The principle of the Ayrton and Mather shunt can be understood from Fig. 46. Here G is a galvanometer of resistance G, TT' the resistance which is connected to the galvanometer terminals and forms the shunt proper, B a source of current, C the current (total) flowing through the battery circuit, c the current flowing through the galvanometer circuit, and R the resistance of the conductor, $TT.'$ From the law of divided circuits the current that flows through the galvanometer is $C = \frac{r}{r+(R-r+G)} = \frac{r}{R+G}$. When the contact of the source of current is made at the extremities, TT' of the shunt, the current flowing through the galvanometer is evidently $c = \frac{R}{R+G}$. If, therefore, r be made $\frac{1}{10}$ of R, only $\frac{1}{10}$ of the battery current goes through the galvanometer, and the deflection for a given battery current is reduced to $\frac{1}{10}$. If r be made 01 of R, only $\frac{1}{100}$ of the battery current goes through the galvanometer, and the sensibility is reduced to that amount. A commercial form of Ayrton and Mather shunt is illustrated in Fig. 47. Here there are four steps giving sensibilities of 1, $\frac{1}{10}$, $\frac{1}{100}$ and of $\frac{1}{1000}$ the normal with two additional steps, one short circuiting the galvanometer when no current is on, and the other opening the galvanometer circuit itself. By means of the small hard rubber handle shown, the contact carriage may be quickly moved along the line of contacts, the galvanometer being watched at

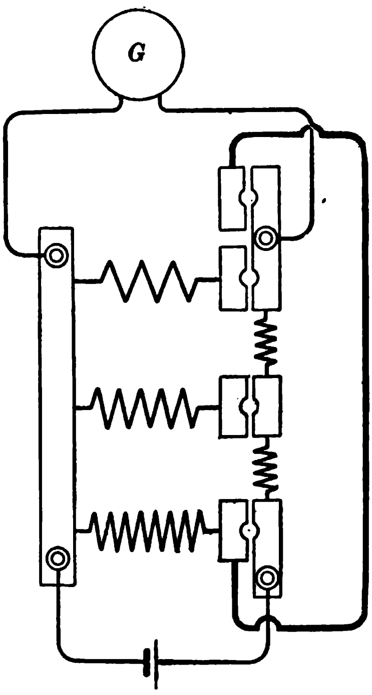

FIG. 45.

the same time, until a sensibility is reached which gives a good deflection.

ERECTION AND CARE OF GALVANOMETERS.

Generally speaking, the higher the electrical sensibility of a galvanometer, the more it is subject to the influence of mechanical vibration, and, if placed on an ordinary work-bench or table, it is out of the question to use one in a workshop; for the trembling of the mirror causes the spot of light to jump over the scale in such a manner that no readings can be taken. A frequently adopted plan to overcome this annoyance is to build a heavy brick or stone column, capped with a slab of soapstone or slate, on which the galvanometer may be placed and leveled for use. In order to prevent the communication of the vibrations of the building thereto, this masonry pier must be carried clear down into the ground, and must be kept free throughout its whole length from contact with any part of the building. This expedient, of course, is expensive, and local conditions are sometimes such that even it does not afford a complete remedy; moreover, the construction of such a pier for use in the upper stories of a building is out of the question.

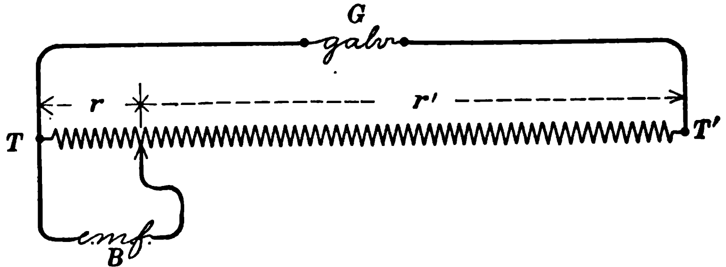

FIG. 46.

In most circumstances, as good or better results can be secured at a less expense, by mounting the galvanometer on a heavy timber or stone shelf built solidly into the walls of the building, provided the machinery foundations are separate from the foundations of the walls. With a reasonably well-built structure, and not too much moving machinery on the floors, good results may be obtained some stories from the ground.

In cases where this plan does not give a sufficiently steady support, the galvanometer may be mounted on a platform hung from springs, and provided with suitable weights. The proper adjustment of the weight, with respect to the strength of the suspending springs, is the principal feature in making a success of the method. The springs should be rather long, moderately strong, and should then be loaded down so as to stretch them well. Thus adjusted, the natural period of oscillation of the apparatus, as regards vertical displacements, is large, so vertical tremors of a comparatively high frequency are, practically speaking, completely damped out. High frequency disturbances in a horizontal plane are still more completely gotten rid of.

FIG. 47.

Should there be a tendency for the apparatus to oscillate in its natural period, pendulum-wise or vertically, it can be overcome only by the use of dash-pots or their equivalent. These may be arranged to damp either a vertical or horizontal oscillation. Another good way to damp horizontal movements of long period is to fasten rubber bags below the platform, in such positions that they may be brought into contact with the under side of the platform by inflating them with air. This will stop the long period movements, while the bags are not sufficiently rigid to communicate short period movements.

Fig. 48 shows a double platform. On the upper shelf is placed the principal weight, while the galvanometer is placed on the lower shelf. The weights and springs should be so adjusted that the natural periods of the two shelves are incommensurable, which still further tends to damp out vibrations of all frequencies. This arrangement is, however, necessary only under exceptionally unfavorable circumstances.

The scale on which the deflections of the beam of light from the galvanometer mirror read off is placed on a separate support, as, in the case of the pier or shelf arrangement, a support large enough to contain both would be too costly, and, in the case of the spring suspension form, both bulky and offering a chance of trouble if the scale should be accidently touched by the observer, as this would then set the whole apparatus in vibration. A

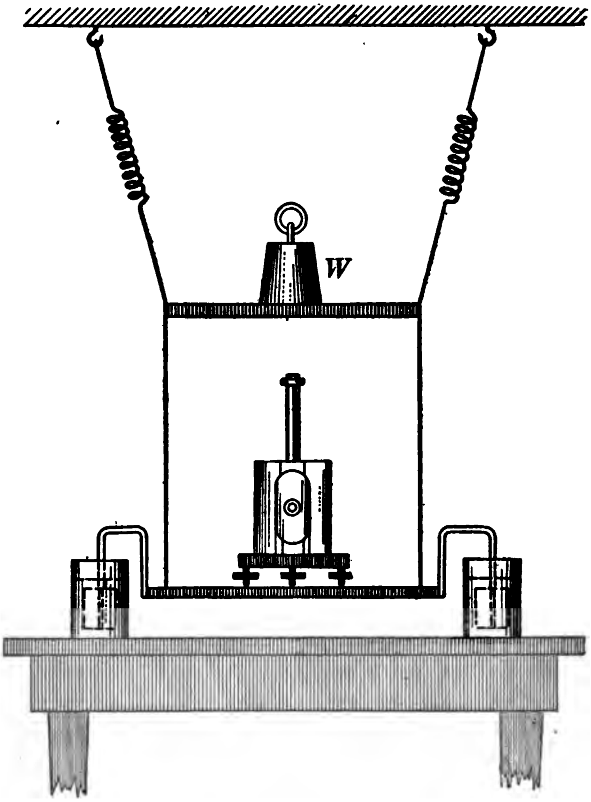

FIG. 48.

small vibration on the part of the scale is of little importance, as it is not magnified in the same way that the light beam motion is, and the scales are, therefore, usually mounted on a simple standard at the proper distance from the galvanometer, or, in special cases, may be supported from overhead.

In that form of reading device in which a telescope is employed, the only requisite is that the general illumination on the scale be sufficient to make the scale markings, as reflected in the mirror, and viewed through the telescope, readily visible. In the pattern where a beam of light is thrown on the galvanometer mirror, and reflected from there by a translucent scale, the apparatus must, of course, be placed in a room, which, while it need not be absolutely dark, must have but a low illumination in order that the position of the line of light on the ground glass may be readily discerned. The source of the beam of light may be an oil lamp or a gas jet, inclosed by a metal chimney, having a fine slot in one side through which the ray emerges. This is condensed by a lense and thrown on the mirror, the latter being concave to prevent dispersion, and makes a sharp line on the scale. In order to obtain a darkened galvanometer room, hangings are usually used, which interfere with the circulation of the air, and the room is apt to become stuffy, if gas or oil flame is employed. It is therefore still better to use an incandescent lamp as the light source where possible. The lamp should not have a filament of the coiled form, but one of the old plain U shape, and the shield around the lamp arranged so that the light from the straight portion of one of the halves of the U is what is allowed to fall on the mirror. Some foreign makers go so far as to construct a special incandescent lamp for this work, in which one leg of the filament is made absolutely straight. An example of this is illustrated in Fig. 49.

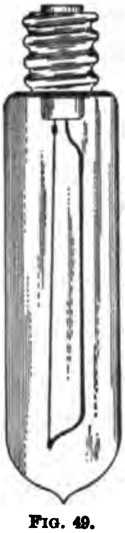

FIG. 49.

Few general instructions can be given in a work of this kind as to the care of a galvanometer, because the constructional details vary in instruments of different makes, and where complete instructions are not supplied with the apparatus by the builders, the application of common sense will remedy the defect.

Those not accustomed to handling such work will have their patience sorely tried, when a suspension breaks and must be replaced, but they must console themselves with the reflection that even experienced users break many a new suspension when replacing an old one.

CHAPTER IV.

POTENTIOMETERS.

SLIDE WIRE TYPES.

THE potentiometer is an instrument of precision for electrical measurements that is sufficiently important to warrant devoting an entire chapter to its uses. With its aid, and that of certain auxiliary appliances, measurements of potential may be made in terms of the E.M.F. of a standard cell, covering a range of from a very small faction of a volt to several thousand volts, and of currents from a fraction of an ampere to many thousand amperes. It may also be used for the accurate comparison of resistances, and therefore indirectly for the measurement of temperatures varying from below freezing to 1,200° C.

The principle of the ordinary potentiometer may be understood by reference to the accompanying Fig. 50. Here *MN* is a straight wire of convenient length and as high resistance as possible consistent with mechanical durability. To its ends are attached leads from a battery, *B*, usually a storage cell giving a potential of about two volts, in circuit with an adjustable resistance, *R*, by means of which the difference in potential between the points *M* and *N* may be adjusted to any desired value lower than the cell potential. To the point *M* there is also connected a wire running to one pole of a double-throw switch, *D*. By means of a suitable device, *C*, contact may be made at any desired point along the wire, *MN*. The connection running from the contact, *C*, passes through the galvanometer, *G*, to the other pole of the double-throw switch, *D*. When *D* is thrown to the position shown in the figure, it connects the wire terminal attached to one end of the wire, *MN*, with one pole of a standard cell, *S*, and the adjustable contact, *C*, with the other pole of that cell. When the switch, *D*, is thrown to its other position, the same points are connected with the unknown E.M.F. to be measured. The standard cell has a resistance, *r* (usually about 10,000 ohms), connected in series therewith, which resistance may be short circuited by the switch shown, and the galvanometer is provided with a shunt, *S*, which may be cut in or out by means of its switch. When a potential measurement is to be made, the switch, *D*, is thrown so as to couple in the standard cell, the resistance, *r*, being in the standard cell circuit, and the shunt, *S*, across the galvanometer terminals. If the wire, *MN*, has an adjacent scale divided into 2,000 equally spaced divisions, and the E.M.F. of the standard cell at the temperature at which it is being worked is 1.434 volts, the contact, *C*, is placed 1,434 divisions away from *M*, and the rheostat, *R*, varied until the galvanometer shows no deflection. The shunt, *S*, across the galvanometer terminals is then cut out so as to increase the sensibility, and if the galvanometer then shows a small deflection, the rheostat, *R*, is further adjusted until that deflection disappears. As the strength of the current from the battery, *B*, through the wire, *MN*, is now such that it causes between 1,434 of the 2,000 spaces in which that wire is divided, a drop of potential of 1.434 volts, the difference in potential between *M* and *N* is evidently two volts. If therefore the switch, *D*, is thrown over, so as to apply to the points, *M* and *C*, an unknown potential, which

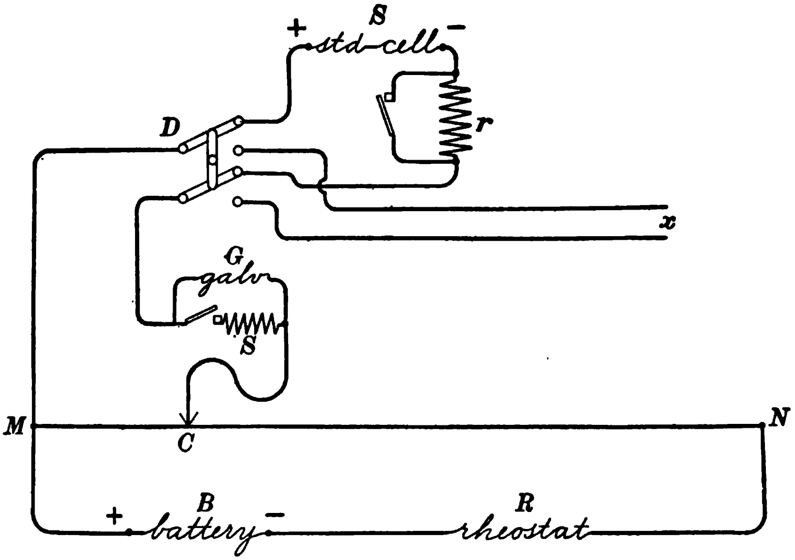

FIG. 50.

must, of course, be less than two volts, and the contact, *C*, is moved along the wire until the galvanometer shows no deflection, the E.M.F. of the source to be measured is given directly by a number of the divisions between *M* and *C*, each of which divisions represents .001 volt.

In actual practice the length of the wire, *MN*, is usually made about one meter. If it is longer the apparatus becomes awkward to handle, and if much shorter it is extremely difficult to read its scale, with 2,000 divisions, without straining the eyes.

A more practical form of potentiometer is diagrammatically shown in Fig. 51. It will be noticed that this differs from the elementary one in that the resistence between the points *M* and *N* is no longer composed of a single straight wire, but of fourteen coils of wire, each provided with an appropriate terminal, plus the straight wire. The resistance of each of the coils is the same as that of the straight wire, *MN'*, and both of the wires running to the multithrow switch terminate in contacts which may be moved along the resistance, *MN*. In this form, if the rheostat *R*, be adjusted so that the difference of potential between *M* and *N* is 1.5 volts, the fall of potential between the terminals of each of the fourteen coils is one tenth of a volt, and if the wire, *MN*, be divided into 1,000 divisions, the difference of potential between each will be $\frac{1}{10000}$ of a volt; in other words, the arrangement is made ten times as sensitive as the elemen-

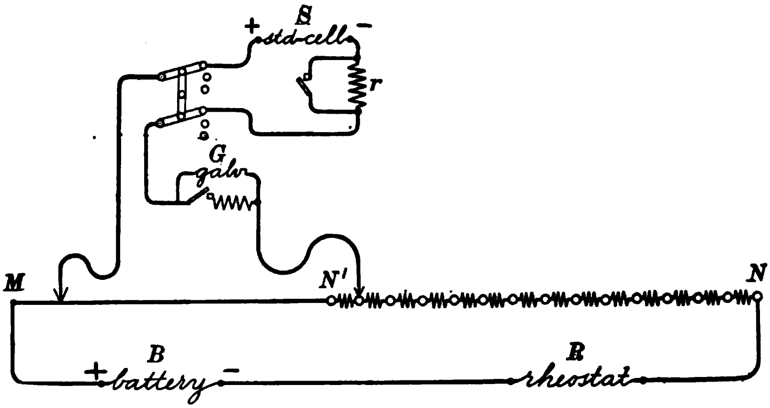

FIG. 51.

tary form by the addition of supplementary coils. The length of the wire, *MN*, may be made somewhat less than a meter, but if the apparatus is to be used for considerable periods at a time, the length should not be less than two feet, because of the strain on the eyes of the observer, due to the fineness of the divisions.

The modified form has an additional advantage over the elementary, in that the resistance between the points *M* and *N* is far higher, and there is therefore less current drawn from the battery *B*, with a consequent less liability of change in strength of that current. In both it is essential that the straight wire be of uniform resistance throughout its length, in order that the drops across equal portions thereof may be uniform.

Calibration of the Slide Wire.

As the accuracy of a slide wire potentiometer depends fundamentally on the assumption that the wire is of uniform resistance throughout its length, and as the results given by it are erroneous unless this holds rigorously correct, it is well that a user should know how to investigate this point for himself.

Accurate checking is at best a tedious process, the following being probably the most convenient method: First, two standard resistance coils of a value which may conveniently be in the neighborhood of one ohm each are selected, and these must then be adjusted so that their resistances are exactly alike. This is usually accomplished by shunting the higher resistance one with a plug resistance box and altering the box resistance until the two are shown by any convenient one of the methods described in the chapter on resistance measurements to be exactly the same. That fine adjustments are possible in this manner is evident from consideration of the fact that if the box has a resistance of as low as say 2,000 ohms, and this is placed in shunt to one ohm, the combined resistance becomes $\frac{1 \times 2000}{2001}$ ohms, or approximately, .9995 ohms, a variation of .05 per cent.

Having by such means obtained two exactly equal resistances, adjust one of them so that its resistance differs from that of the other by a very small but definite amount, which it may be assumed is obtained by shunting it with 1,000 ohms. If each of the resistances were originally x ohms, the one shunted by

1,000 ohms becomes $\frac{1000\,x}{1000+x}$ and the difference between them, $x - \frac{1000\,x}{1000+x}$ ohms. The two coils differing by the known amount, derived from the above formula, are then used as the coils *A* and *B* in the arrangement shown in Fig. 52, which figure will be understood to be merely diagrammatic. In the same figure *ab* form the terminals to which the extremities of the wire under test are secured and *e* and *f*, terminals for another bare stretched wire, whose resistance per unit of length need, however, not be uniform. A battery and a galvanometer are also provided as shown. The galvanometer contact *G* is now moved along the wire *ef*, until the galvanometer shows no deflection, with the contact *C* kept constantly at position 1; this point is noted, and the coils *A* and *B* interchanged. The galvanometer can again be brought back to zero by moving *C* to the point 2. The distance between the points 1 and 2 of the wire under test is then the difference of the resistance of the coils *A* and *B*. The coils *A* and *B* are now put back in their original positions, and *C* being kept at the point 2, the contact *G* shifted to another position, *G′*, on the wire *ef*, where balance is restored. This evidently forms a fresh starting point, and the resistance of the section 2-3 of the wire under test may be found in terms of the difference between the resistances *A* and *B*. The process is repeated until the whole wire *ab* has been divided up into sections of equal and known resistance. If these coincide with the scale markings on the potentiometer as secured from the maker, it may safely be presumed that the wire

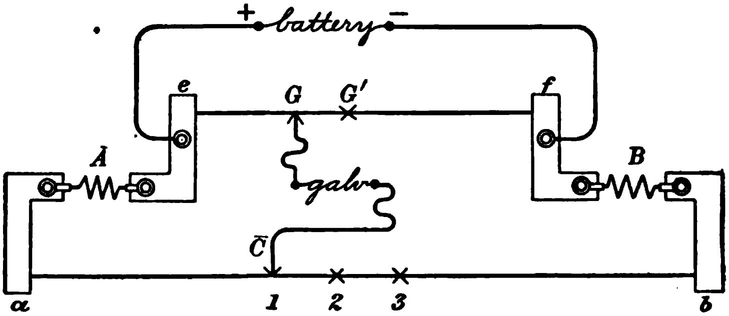

FIG. 52.

has been properly tested for and adjusted to uniformity, or else that the scale has been drawn to allow for inequalities in the wire.

When calibrating a wire that has not been checked before, it is usually advisable to make the above test more than once, using fresh values of difference in resistance between *A* and *B*, in order that the measurements will include practically every section of the wire length.

A rougher test of the uniformity of resistance of a slide wire may be made by passing a continuous current of an appropriate constant strength through it and then by means of a pair of contacts held rigidly spaced at a small distance apart, observing whether the deflections of a galvanometer attached to the contact terminals are the same wherever on the wire length the contact may be applied. If they are, the wire is evidently electrically uniform.

Contact Devices.

The device used to make contact with a potentiometer wire must be carefully constructed in order that its position with reference to the fixed scale may be accurately read off and that the operator cannot mar the wire when making contact, and thus destroy the uniformity of its resistance. The form of contact used in the old model Crompton potentiometer, which instrument is built on the principle illustrated by Fig. 51, is illustrated in Fig. 53. Here *S* is the extremity of a long weak spring, which tends to press downward the wedge-shaped block secured to the end of the spring. The downward tendency of *S* is more than overbalanced by the upward pull on it exerted by the button-shaped head of the plunger, *P*, beneath whose shoulder there abuts a spiral spring. *P* is the knob that is depressed by the operator when it is desired to make contact with the wire and the exertion of considerable pressure on the knob, *P*, will not increase the pressure of the contact on the wire, as *P* simply releases the weak spring that carries *S*, and the pressure on the wire is determined solely by the elasticity of that spring. The knurled-headed screw pro-

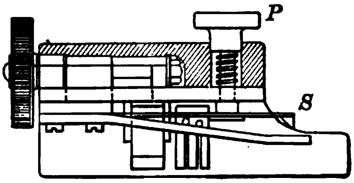

FIG. 53.

jecting from the end of the contrivance works a micrometer screw to make very fine adjustments. An even more elaborate form of contact is shown in Figs. 54 and 55, this being one designed by Callender and Griffiths for use with their laboratory standard bridges. It is made in two parts, one of them, *ABA′*, sliding against the non-graduated guide bar that is placed parallel to the graduated scale, and the other against the graduated bar. The first part is steadied by means of springs, placed as shown, that keep it in contact with its guide, and the second piece in a similar manner has a flat spring between it and the first. To the section *ABA′* is attached a bracket carrying the screw *S*, which is used to make fine adjustments. When this is turned, the inner block, *E*, alone moves, as its pressure against the graduated bar is only that due to the spring at *EE′*, whereas the pressure of the outer portion against the guide bar on which it slides is the pressure exerted by the spring *EE′*, plus that of the springs at *AA′*. The wire, *W*, is brought into contact with the sliding wire itself, and the one parallel to it attached to the galvanometer terminal by turning the screw, *C*, and forcing the slide and galvanometer wires down on one running at right angles thereto. By this means a very definite point of contact may be obtained. It is very difficult for a careless operator to injure the potentiometer wire with this form of bridge, for if it were attempted to move it without releasing the screw, *C*, the outer block, *ABA′*, would simply move relative to the inner one without tearing or deforming the wire.

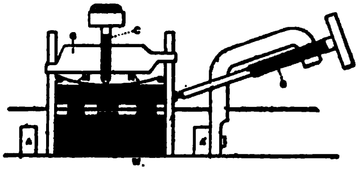
FIG. 54.

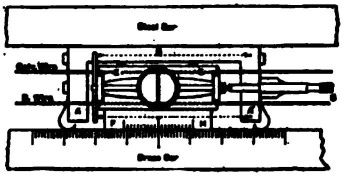
FIG. 55.

In commercial potentiometers where laboratory accuracy is not required and the item of cost comes into consideration, it is becoming more common practice to use a simpler form of contact in connection with the slide wire. This device is continually in contact with the wire, and is simply slid along from one position to the other when readings are being made. Such contacts usually take the form of rather blunted knife edges at right angles to the wire length, being pressed against the slide wire by a weak spring and supported by a rigidly guided block. The spring tension must be adjusted with great care to avoid the wear on the slide wire that would ensue if it were too great, and the uncertain contact that would exist if it were too small. The spring adjustment is usually fixed by the maker of the instrument and no means are provided by which the user can change it later on.

With the constantly engaged form of contact it is necessary to be particularly careful to see that both the wire and contact are perfectly clean, as any grit would cause rapid and, of course, uneven wear, which would destroy the uniformity of the resistance of the wire, and hence the accuracy of the whole device. In the present type of the Crompton potentiometer, which is probably the best known of the slide-wire type instruments, the wire itself, as well as all other moving contacts, are, as is shown by Fig. 56, completely enclosed and shielded by plate glass.

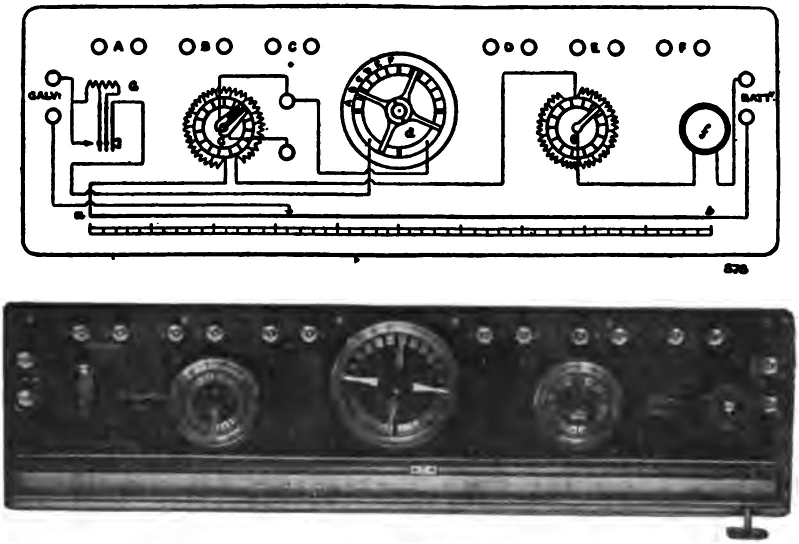

FIG. 56.

In one form of the Leeds and Northrup instrument, shown in Fig. 57, the slide wire is exposed on the surface of the marble drum about which it is wound in a manner that renders it easily accessible for cleaning with a soft cloth, or fine tissue paper. In both instruments it is necessary to keep the wire coated with a thin film of vaseline or paraffine oil, as this is found to eliminate the otherwise troublesome thermal E.M.F's set up at the point of contact and, of course, diminishes the wear.

In a later design of the Leeds and Northrup potentiometer, the marble drum is covered by a cylindrical shield to protect it from dust.

All potentiometers of the slide-wire type are somewhat objectionable in that their necessarily low resistance means that a fairly heavy current is required from the working battery, a condition that involves more rapid polarization with a consequent change in the drop along the wire. To check up the correspondence of the wire and its scale is further, as is evident from what has before been said, an extremely tedious operation, and one calling for auxiliary apparatus of a kind that is not always available. On the other hand, the low resistance potentiometer is better suited for making measurements of very small potentials, and being continuously adjustable, has an infinite number of steps in contrast to any step by step design.

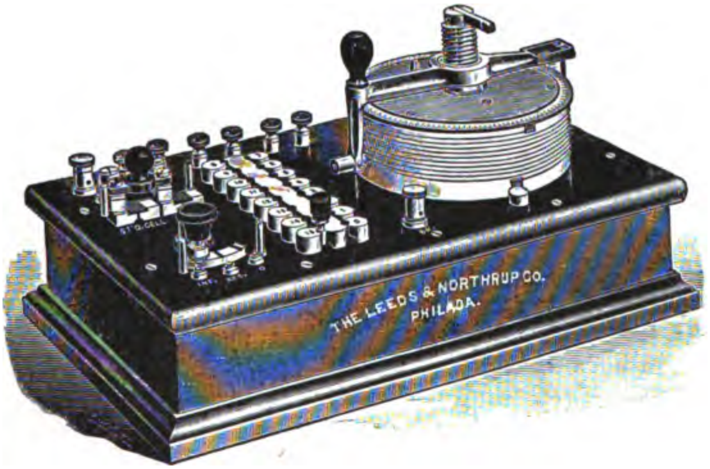

FIG. 57.

RESISTANCE COIL POTENTIOMETERS.

Potentiometers having a relatively high resistance may be made by substituting for a straight wire a set of resistance coils electrically connected in series, and with their terminals attached to contact plates or buttons.

If it be desired to work to the fourth or fifth decimal place the number of coils that would be required, if a separate one were provided for each step, would be prohibitively large, one thousand, for instance, being needed to replace the slide wire alone if the wire scale of the Crompton instrument was to be duplicated.

To avoid this a modification of the Varley slide, which is analogous to the vernier used in mechanical measurements, is used. Referring to Fig. 58, in which the apparatus is diagrammatically illustrated, between the points *A* and *C* there are fourteen coils, each of 1,000 ohms resistance, connected to the terminal contacts shown. Between the points *C* and *B*, 10 resistances of 10 ohms each are similarly connected. Between *E* and *F* there are 9 coils, each of 1,000 ohms resistance, and between *G* and *H*, 9 coils, each of 10 ohms resistance. The terminals of *EF* and *GH* are connected to a pair of contact points, *MM* and *M'M'*, respectively, rigidly coupled together by means of an insulating piece, and held separated by a distance equal to the space between the contact buttons of the coils composing *AC* and *CB* respectively. Referring first to section *AC* of the apparatus, the drop of potential between the buttons under *MM* is evidently that due to the flow of the current through a circuit composed of 1,000 ohms resistance shunted by 9,000 ohms, namely, a circuit of

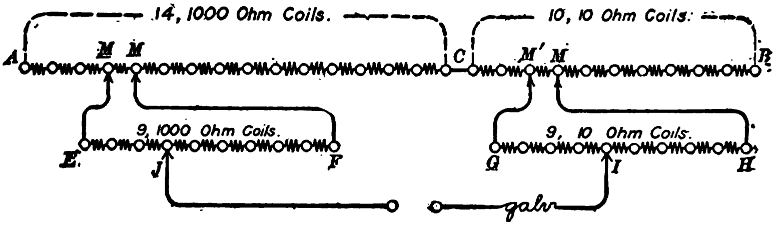

FIG. 58.

$$\frac{9000 \times 1000}{9000 + 1000} = 900 \text{ ohms.}$$

As this drop is that between *E* and *F*, which in turn is composed of a series of nine equal resistances, the drop between any two buttons on *EF* is evidently that due to the current flowing through a resistance of one ninth of 900 ohms, namely, 100 ohms. In an exactly similar way the drop between the contact buttons of the resistance forming the series *GH*, is that due to the current flowing through 1 ohm. In other words, if adjustable contacts be made to slide over *EF* and *GH*, the total drop may be varied in four steps, the unity steps being caused by shifting the contact, *I*, along *GH*, the tens steps by shifting *M′M′* along *CB*, the hundreds steps by shifting *J* along *EF*, and, finally, the thousands steps, by shifting *MM* along *AC*. The total range is made to take in 1,500 units in order that the value of the E.M.F. of the standard cell to be used for comparison purposes may be set off directly to steps corresponding to a resistance of 1,434 ohms if the Clark cell is used, or 1,019 ohms if the Weston cell is used, whereupon any E.M.F. to be measured in terms of the standard cell could be read directly by steps of .0001 volt each.

The resistance of the contracts at *MM*, *M′M′*, *J*, and *I* introduce errors that are inappreciable. Taking, for instance, the case of the contacts M′M′, if these had a resistance as high as 0.1 ohm, the 10-ohm coil, to whose terminals connection is made, is shunted by 90.1 ohms instead of 90 ohms, and the resultant resistance is $\dfrac{1}{\frac{1}{10}+\frac{1}{90.1}} = 9.001$ ohms instead of 9 ohms, which is an error of only about .01 of 1 per cent.

As the resistance coils entering into the construction of this type of potentiometer are all of either ten or one thousand ohms value, it is a very simple matter to check the adjustment at any time as almost every testing installation includes apparatus by means of which resistances of this order may be compared with a high degree of accuracy. Each contact button usually has a hole drilled in it at some convenient point and is provided with a set screw, so that it is easy to attach wires to the terminals of each individual coil to measure its resistance.

It should be noted that it is not essential even that standard resistances of 10 and 1,000 ohms respectively, be available, as all that is necessary in order to have the apparatus read correctly is that all the 1,000 ohm resistances shall be alike and all the 10 ohm resistances alike, and equal to one one-hundredth part of the nominal 1,000 ohm resistances. Any one of the coils may, therefore be used as the standard of comparison, and if the others agree with it the apparatus is in proper shape.

Leeds and Northrup Potentiometer.

A potentiometer of the step by step type using the Varley slide, is shown in plan view in Fig. 59, the connections of the same being illustrated by Fig. 60. It will be observed that the series of coils in the right-hand side of the figure, that is to say, between *C* and *B*, is provided with a slide on a slide, thus increasing the number of readable steps to 15,000. A feature of great convenience in this potentiometer is the arrangement for throwing in the standard cell for making the initial adjustment of the rheostat *R* in the working cell circuit and of allowing the checking at any instant of the fact that the current sent through the potentiometer by the working cell has remained unchanged, both without necessitating a resetting of the five radial switch arms to the positions corresponding to the standard cell voltage.

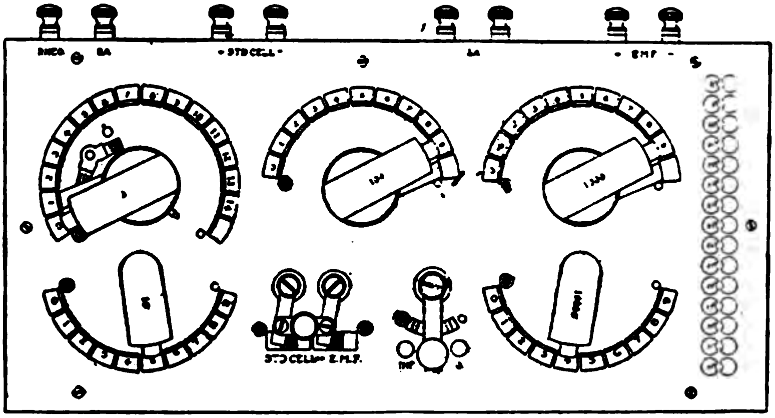

Fig. 59.

This is accomplished as follows: In Fig. 60 the resistance of the fifteen 1,000-ohm coils between *A* and *C*, one of which is always shunted by 9,000 ohms, is 14,900 ohms, and of the ten 10-ohm coils in *CB*, as shunted by the double slides, 99.9 ohms, a total of 14999.9 ohms.

Now, assuming that a non-saturated solution Clark cell is to be used as the standard, the maximum temperature at which this will be employed would hardly exceed 32° C., at which point its E.M.F. would be, according to the formula before given, 1.4355 volts.

Now, if the standard cell were at *E* and the double pole-switch *U* in the position shown, the various slides would have to be set to positions making the drop at the cell terminals, that is, across 14,355 ohms, in order that when the working cell current was adjusted by the rheostat, *R*, so that there would be no deflection of the galvanometer, *G*, when the key, *V*, was closed, the drop per readable point on the potentiometer should be exactly .0001 volt.

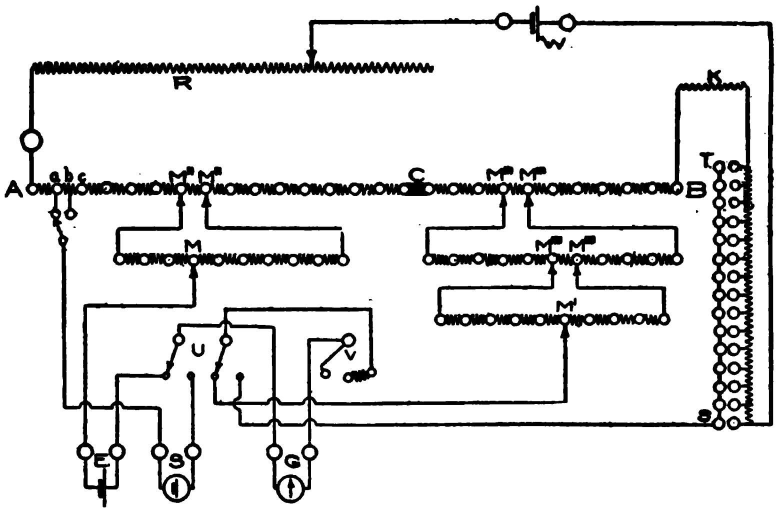

FIG. 60.

By simply shifting the double pole-switch, *U*, to its other position, however, it will be seen that no matter where the slides may be placed (with a single exception to be noted presently) the resistance across which the cell terminals is connected is *AC* (13,900 ohms), plus *CB* (99.8 ohms), plus *K*, which latter is made 355.1 ohms, a total of 14,335 ohms, or just what is required. To allow for the increased E.M.F. of the standard cell with decreasing temperatures, the series of coils between *T* and *S* is added, the value of each coil being made such that when the plug shown in the diagram as at *T* is shifted to another position, stamped as shown in Fig. 59, with the different temperatures that the cell may have, the total resistance between the terminals of *S* is added to sufficiently to effect the necessary compensation.

The one position of the slides at which the resistance of the series *AC* is not 13,900 ohms, is when the slide for that series spans the first coil, *Aa*. To avoid its being necessary for the operator to make inspection each time to see that the slide is not in that position when making a standard cell setting or check, the coil *ac* is divided into two sections, *ab* of 100 ohms, and *bc* of 900 ohms. The small single pole-switch shown at that point and clearly illustrated also in Fig. 59 is mechanically interlocked with the slide arm lever in such a manner that when the latter is at the position *Aa* it connects the standard cell to *b*, and when the slide is at any other position it connects the cell to *a*. Of course, when the standard cell is of a type having some voltage other than that of the non-saturated solution (Clark) the value of the resistance at *K*, and, if necessary, the point of attachment of *a*, is appropriately changed at the time that the apparatus is built. If the cell has no temperature coefficient, the coils *TS* are omitted.

Other potentiometer constructions which maintain a constant resistance of the working cell circuit and at the same time allow a shifting of the points at which contact may be made along that circuit are feasible, and, in fact, in some use, but the two above described are the most common and the best suited to ordinary requirements.

Before leaving the general subject of the potentiometer method of measurement, it may be well to point out that one reason for the great accuracy attainable thereby is that it is a zero method, that is to say, the results are obtained when a galvanometer shows an absence of current rather than when it gives a certain deflection. In this way errors due to variations of magnetic force when measurement is going on, to alterations in resistance of the galvanometer circuit because of temperature changes, to an alteration in the restoring force of the galvanometer system, to a change in potential of the standard cell due to drawing too great a current from it, and to varying contact resistances, are all eliminated.

The Lorenz apparatus for the determination of resistance in terms of the fundamental units, as described on page 6, is an example of the potentiometer system of measurement as is likewise the method of plotting the wave forms of alternating currents described on page 259. Other applications are numerous.

MEASUREMENT OF E.M.F. WITH A POTENTIOMETER.

The method of measuring the difference of potential between any two conductors led to a potentiometer is fairly obvious from the foregoing descriptions of this class of apparatus. The procedure involves, first, the establishment of a known difference of potential per step, if the potentiometer is of the step by step type, or per scale division, if of the slide wire type, by adjusting the strength of the current supplied by the working cell until the standard cell voltage is exactly balanced by the drop over the number of steps or divisions equal to its voltage.

The unknown E.M.F. is then applied to the series of resistances by manipulating the sliding contacts until a point is found where no current flows through that branch circuit, whereupon it is known that the difference of potential between the ends of the circuit is the same as that existing across that number of steps of the potentiometer.

Volt Boxes.

It is obvious that none of the potentiometers so far described is suitable for the measurement of potentials in excess of 1.5 or 2 volts. To measure higher ones, devices called "volt boxes" are used, which are simply coils of wire of high resistance having terminals attached so that one half, one tenth, one one-hundredth, or any other desired fraction of the total E.M.F. between the volt-box terminals exists between the one end of the volt coil and the lead selected. Where the potentiometer is to be used to cover a wide range of measurement, the volt box is made to contain several coils, often having a resistance of 50, 50,400 and 9,500 ohms respectively, connected in series as shown in Fig. 61. From this figure it is evident that if the leads to the potentiometer be attached at *a* and *b*, a difference of potential as high as 300 volts may exist between *a* and *e* without making the E.M.F. applied to the instrument come above its maximum capacity of 1.5 volts, in other words, the volt box is at that step a multiplier of 200. If the potentiometer connection be made at *a* and *c* the potential difference between *a* and *e* may be as high as 150 volts without exceeding the potentiometer's capacity, and the volt box acts as a multiplier of 100; similarly, the step *ad* forms a multiplier of 20, permitting the measurement of potentials up to 30 volts.

When the voltage to be measured is over 1.5 and less than 3 volts, the range of the potentiometer itself may be temporarily doubled by using two standard cells in series instead of one, and two working cells in series instead of one, the value of the potential difference per scale division being thus doubled. This, however, means the passage of a current of twice the normal strength through the potentiometer, and it should first be ascertained whether the device can safely withstand that overload.

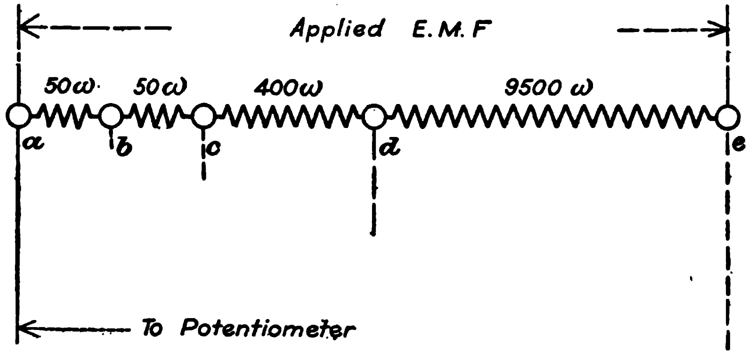

FIG. 61.

CURRENT MEASUREMENTS WITH THE POTENTIOMETER.

Currents are measured with the aid of the potentiometer by determining, in terms of the E.M.F. of a standard cell as usual, the drop in potential across a known standard resistance, traversed by the current whose strength is to be ascertained, and then calculating the current from Ohm's law. Such standard resistances must, of course, be selected to have a value which will give a sufficiently large drop when traversed by the current to enable this to be accurately read, and must also have a section large enough to carry that current for a sufficient time to make the test, without heating to an extent that appreciably increases the resistance.

While such standard low resistances, or shunts, as they are sometimes called, are usually purchased by a user as a finished piece of apparatus, it may not be out of place to point out some of the precautions that must be observed in their proper design, as these have some bearing on their use. Moreover, it is sometimes desirable to extemporize a shunt, as can readily be done by taking a suitable resistance and calibrating it by measuring its value in terms of any of the sizes of shunts already on hand by the potentiometer resistance measuring method to be described presently, and in that case a failure to observe the precautions is apt to make the results inaccurate.

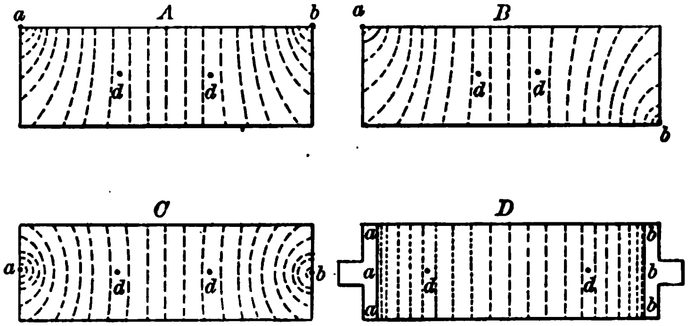

Fig. 62.

Standard Low Resistances.

Standard low resistances, then, may not consist of a simple sheet of resistance metal through which the current to be measured is passed and between any two equidistant points on which the drop is taken, unless the points of attachment of the main and potential wires are always the same. This is because the current flowing through a sheet will distribute itself differently with different points of attachment of the terminal wires. Fig. 62 illustrates this point. Here *A* is a resistance sheet into which the current is lead by a terminal, *a*, secured to the upper left-hand corner, and out again through the upper right-hand corner, *b*. *B* shows the same plate with the current led in and out through diagonally opposite corners, and *C*, the same thing again, but with the current conducted through it by conductors attached to the center of the plate at each end. The curves in the figures are lines connecting the points of equal potential as found by actual measurement with a galvanometer and exploring points, and are credited by Mr. Fisher to Mr. A. C. Keep. The author has made similar tests which substantiate these. The proper current distribution in the plate is attained only by working along the lines shown in *D* of the same figure, where there are heavy terminal blocks, either of another material than the resistance sheet, or else heavy masses of the same material. Even with this form care must be taken in proportioning the terminals, for if their size be insufficient or the resistance of the attached lugs too high, the distribution may be affected to an appreciable degree.

Another important consideration is the location of the contact points where attachment is made to the potentiometer or other apparatus for measuring the drop due to the current flow. In shunts for commercial indicating instruments where the highest accuracy is not required, it is not uncommon to attach these drop studs to the terminal blocks, as by this means a maximum drop is obtained and a saving in material is effected. This location is not only apt to bring the drop studs to a position where the equipotential lines are disturbed when current is led into and out of the terminal blocks at different angles but to introduce thermoelectric potentials, which, whether they be opposing or assisting the drop due to the current, of course introduce errors. These foreign potentials are generated for the following reasons. The material of the resistance strip is ordinarily different from that of the terminal blocks, the latter being usually of copper and the former of some resistance alloy like manganin or German silver. If the temperature at the junction between the resistance plate and one terminal lug be the same as that at the junction between the plate and the other lug, the thermoelectric E.M.F. between one of them and the resistance sheet is equal and opposite to that between the resistance sheet and the other lug, and hence there is no difference of potential between the contact points on the lugs due to that source. If, however, as is often the case, one of the junctions be hotter than the other, due, perhaps, to imperfect soldering between the resistance sheet and the lug, or perhaps to a poor contact between the lug and the wire which carries the current, the heat generated thereby being conducted by the lug to the junction generates an E.M.F. The potential between the sheet and one lug becomes, therefore, greater than that between the sheet and the other lug, and the algebraic sum of these potentials, namely, their arithmetical difference, represents a foreign difference of potential that will exist between the points of attachment of the measuring instrument.

The author has known of instances in which these potentials amounted to fully 5 per cent of the difference in potential between the drop studs, due to the full capacity current flow. The objection can be overcome by the simple expedient of attaching the drop stud to the resistance sheet, as indicated at *d*, Fig. 62, instead of the outer lugs. This is at the expense of increased weight and bulk, but safeguards against errors that are large enough to be objectionable when making measurements of any accuracy.

RESISTANCE MEASUREMENT WITH A POTENTIOMETER.

The method of comparing resistances with the aid of a potentiometer is very simple; it consists of coupling together in series a standard resistance and the one under test. A current of suitable strength is sent through these resistances and the drop in potential across them is measured by means of the potentiometer. The resistances, since the current in both is the same, are, according to Ohm's law, in direct proportion to the drops. For such resistance work it is very desirable that the multi-throw switch of the potentiometer be provided with at least three pairs of contacts for making connection with external circuits, one pair being for standard cell, as usual, one for the standard resistance, and the third for the unknown resistance. In this way a simple movement of the switch arm throws in the resistance to be measured, while the drop readings may be taken in such quick succession that there is but an inappreciable chance of any change in the current during the operation.

This system of resistance measurement is capable of a very high degree of accuracy, results that are correct within one part in 1,000 being attainable with very ordinary care. When the resistance to be measured is of a very different order from that of the available standard, the measurements are preferably made indirectly, by first constructing a secondary standard having a value of one tenth, or ten times, as the case may be, of that of the primary one, and working from that, or even a tertiary standard adjusted from it in a similar way. Another method of accomplishing the same end consists in taking the drop from the unknown standard through the volt box already mentioned, and leading only a fraction thereof to the potentiometer. If, for instance, we have a resistance to measure approximately .01 ohm in value, and our available standard is 1 ohm, the two may be joined in series and the terminals of the 1 ohm standard connected to the volt box. If, then, those potentiometer terminals of the volt box are selected that give the ratio of one one-hundredth, the drop across these with a given current flowing through the standard is one one-hundredth of the drop across the terminals of the standard itself, and the same as the drop that would be given when the same current traversed a resistance of .01 ohm value. It is evident that tests made as above are best suited for comparatively low resistance work.

CHAPTER V.

THE MEASUREMENT OF RESISTANCE.

RESISTANCES of different ohmic value must be measured by using different tests if the results are required to be determined to a high degree of accuracy. While there is no hard and fast line of demarkation, resistances may be conveniently divided into three groups, namely, medium resistances, this including those lying between .1 ohm and 1 megohm; low resistances, under 1 ohm; and high resistances, over 1 megohm.

Before considering the various methods and appliances for resistance measurements, it will be best to glance briefly at the laws determining the resistance of electrical conductors grouped in various combinations, as the measurement of such combinations or networks is a very common problem.

When we have several conductors connected in series the fact that the combined resistance of all is the sum of the individual resistances is almost axiomatic.

When the conductors are connected in parallel their combined resistance can be calculated by the formula derived as follows: Referring to Fig. 63 let R_1 be a conductor having a resistance designated by R_1 and R_2 a second conductor having similarly a resistance R_2, the two being joined in parallel as shown; let the current through R_1 be designated I_1 and that through R_2 by I_2, the total current being I. According to Ohm's law we now have

$$I_1 = \frac{V}{R_1} \text{ and } I_2 = \frac{V}{R_2},$$

V being the difference of potential between the junction points A and B.

Let now R be the combined resistance of the two conductors in parallel, that is to say, the resistance that we desire to ascertain. We then have

$$I = \frac{V}{R},$$

or as

$$I = I_1 + I_2,$$

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2}, \text{ or } \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

Where more than two conductors are connected in parallel, their combined resistance may be ascertained by first determining the resistance of one pair from the above formula, finding the combined resistance of this pair and the next succeeding conductor by substituting the value of the pair resistance for that of a simple one, and so on throughout.

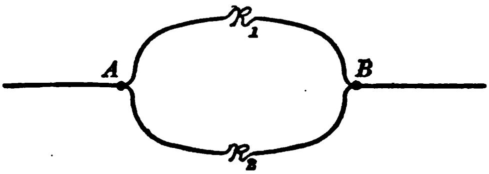

FIG. 63.

As all systems of conductors must be connected either in series or parallel, or combinations of the two, any resistance can be calculated if that of its elements be known, by the application of the above simple principles. However, although the principles themselves are very simple, their practical application to networks of conductors may sometimes involve the solution of complicated equations.*

MEASUREMENT OF MEDIUM RESISTANCES.

THE WHEATSTONE BRIDGE.

The Wheatstone bridge is a network of six conductors, interconnected as shown in Fig. 64. Four of them, lettered *A*, *B*, *C* and *X* respectively, contain resistances only. In one of the remaining branches there is a galvanometer, and in the other a

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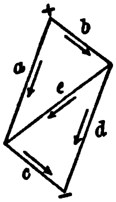

* An interesting example of the foregoing is the calculation of the resistance of the network of five conductors shown in the marginal figure, between the points + and −. At first glance it would seem as if this should be given by a simple expression, but actually the formula, calculated by Townsend Wolcott is:

$$R = \frac{R_a(R_e+R_b)+(R_a+R_b+R_e)\,R_c - R_bR_c\,\dfrac{R_a(R_e+R_c)+R_c(R_e+R_b)}{R_b(R_e+R_c)+R_d(R_e+R_b)}}{(R_a+R_b+R_e)+R_e\,\dfrac{R_a(R_e+R_c)+R_c(R_e+R_b)}{R_b(R_e+R_c)+R_d(R_e+R_b)}}.$$

In this *R* is the total resistance and *R* with subscript letters, the resistances of the respectively lettered branches.

source of current. If, with all the connections as shown, the galvanometer gives no deflection, its terminals are, of course, attached to points in the network which are at the same potential. In these circumstances, if A, B, C and X represent the resistances of the conductors whose identity they respectively indicate, the relation of the resistances is expressed by the equation, $\frac{A}{C} = \frac{B}{X}$. This may be demonstrated as follows: It is obvious, from the diagram, that the current is divided into two branches; one through A and B, the other through C and X. Call the current in A and B, I_1; the current in C and X, I_2. By hypothesis, the drop over A equals that over C, and the drop over B equals that over X. That is,

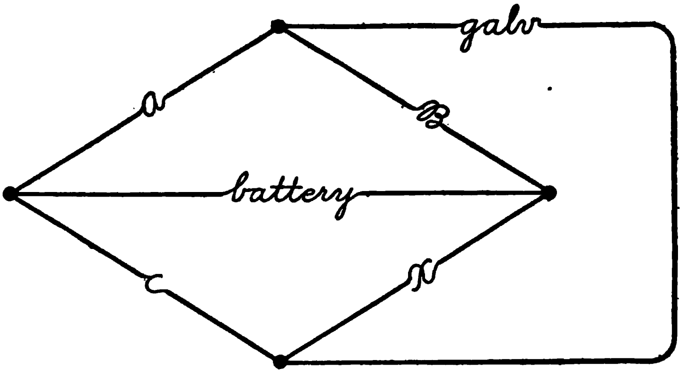

FIG. 64.

$$AI_1 = CI_2 \text{ (1) and } BI_1 = XI_2 \text{ (2).}$$

Dividing (1) by (2), we have,

$$\frac{A}{B} = \frac{C}{X}, \text{ or } \frac{A}{C} = \frac{B}{X}, \text{ as stated.}$$

From the last equation we obtain,

$$X = \frac{BC}{A}.$$

When this condition of balance exists, the conductors containing the battery and the galvanometer are said to be conjugate; the battery and the galvanometer may be interchanged and the resistance of one or both these conductors may be altered without disturbing the balance. This is a most important fact, and is the foundation of several other methods of testing.

If X be an unknown resistance, and the resistance of C and the ratio of the resistance B to the resistance A be known, then X can be calculated. The fact that the ratio of B to A enters into the calculation, makes it possible to cover a large range of measurement with a comparatively limited range of the adjustable resistance, C. If, for instance, B and A be equal, the resistance of X equals that of C. If B be ten times A, X is ten times C, if B be $\frac{1}{100}$ of A, X is $\frac{1}{100}$ of C, etc.

In the commercial form of the Wheatstone bridge, the resistances A and B, commonly termed the "ratio arms" of the bridge and the variable known resistance C, commonly called the "rheostat arm," are geometrically arranged in a different manner from that shown in Fig. 64, in order to economize space; the electrical connections, however, remain the same.

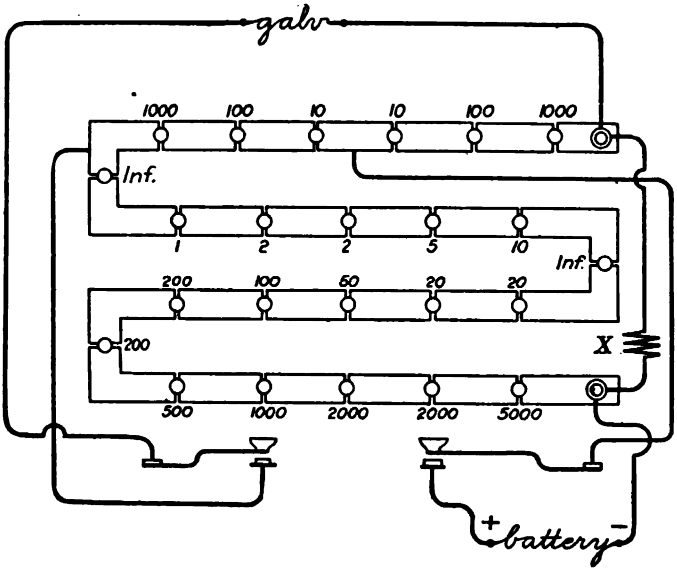

FIG. 65.

Post-Office Pattern.

The arrangement of Wheatstone bridge coils still in most common use is called the "Post-office pattern," it being the form adopted by the British Post-office many years ago. A plan view of a Post-office bridge is given in Fig. 65, the wiring connections being shown by the heavy lines. As will be noted, keys are inserted in the battery and galvanometer circuits, in order that these may be manipulated at the will of the operator. The separate resistance coils forming the bridge and rheostat arms are made as nearly non-inductive as possible, by making each one of a loop of wire, that is, a wire doubled on itself before winding. After being adjusted to the proper resistance the terminals of these loops are soldered to heavy brass blocks, as is shown in Fig. 66. Taper plugs may be inserted, that fit snugly between the members of each pair, which when in place short circuit their respective coils and offer a negligible resistance. To insert given resistance in circuit, therefore, the plug making connections between the two terminals is simply removed.

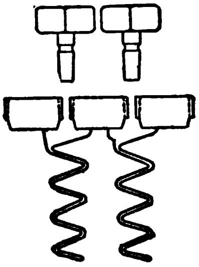

FIG. 66.

It is common to give the resistance coils the value in ohms indicated by the numerals in Fig. 65. As can be seen by inspection of this figure, resistances of from 1 ohm to 11,110 ohms, varying by steps of one ohm at a time, are attainable in the rheostat arm, by pulling out the proper plugs, and the ratio arms may be adjusted from a given value of the *B* divided by *A* ratio, of 100 to 1 to a value of same ratio of $\frac{1}{100}$, thus making the theoretical range of the instrument from 1,110,000 ohms to .01 ohms.

In the original Post-office pattern bridge, the galvanometer, the battery, and sometimes even the galvanometer and battery keys form separate pieces of apparatus. These, plus the bridge itself and the necessary connection wires, form an assemblage of apparatus that is too bulky and awkward to use for ordinary commercial work, particularly when the devices have to be transported from place to place. Combination sets in which the battery, galvanometer, and keys are all built into a common carrying case, and the various wiring connections between them permanently made, are the favorites to-day, except for laboratory work. An instrument of this class is shown in Fig. 67. Here the battery power is furnished by six dry cells arranged in a separate compartment at the right, and cords are fitted in such a way that any number of the cells, from one up to six, may be used at will. The galvanometer is of the class in which the moving system is supported by pivots instead of suspension fibers, and the indications given by a needle playing over a scale, instead of a beam of light, as in the reflecting form. This, while not as sensitive as the other pattern, is sufficiently so to enable readings to be made to a fraction of a per cent when measuring resistances falling within the favorable range of the bridge (.1 ohm to 100,000 ohms). It is compact, does not require accurate leveling, and is sufficiently robust to withstand shipping. A plug-reversing switch lettered *AXBR* in the figure is inserted in the bridge arm circuit. By means of this the connections of the bridge arms to the rest of the network may be reversed. In the present instance this extends the multiplying value of the bridge ratios so as to take in the values 1,000, 100, 10, 1, .1, .01, and .001.

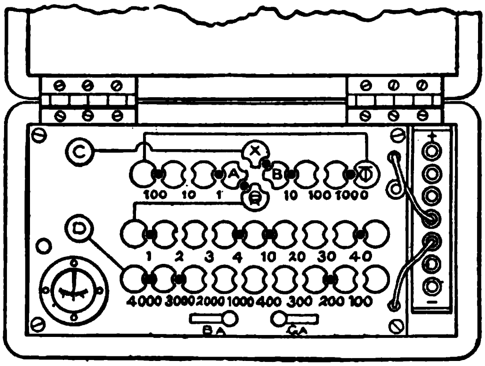

FIG. 67.

As space is such a valuable consideration in these portable bridges, provision can seldom be made for securing specially high insulation of the terminals and key contacts, the hard rubber cover on which all are mounted being supposed to give insulation enough. When measuring high resistances on damp days, however, particularly when a high E.M.F. from some outside set of batteries is being used, to give higher sensibility, the rubber must be very carefully cleansed and dried before making readings, as otherwise the leakage errors may become considerable.

Decade Pattern.

Wheatstone bridges, in which the ratio arms and rheostat values are altered by withdrawing or inserting a plug for each coil, are open to the objection that, small as is the resistance of each individual contact, the total may be comparatively high, particularly after the plugs become slightly tarnished, and the further objection that the continued withdrawal and insertion of a plug tends to loosen, not only the blocks between which it wedges, but the neighboring ones as well, thus making it necessary to go over a whole row each time that a plug is moved, to make sure that the others have not been affected. There is also such a large number of plugs that it becomes a very easy matter to mislay one or more of them when making a test.

It is possible to overcome these drawbacks to a considerable extent by using a "decade" type of bridge in which the rheostat arm resistances are arranged, as shown in Fig. 68. Here, as can be seen, a resistance is cut in by inserting instead of withdrawing a plug, and there is only one plug with its corresponding contact, to each unit, ten, hundred, or thousand numeral in the total. In addition to this, the decade arrangement is convenient because it is formed of groups of coils, in which each member of a group has a resistance which is the same as that of all the other members of the group, and if terminals are provided so that leads may be attached to these resistances, the various coils may be intercompared without its being necessary to have recourse to outside standards.

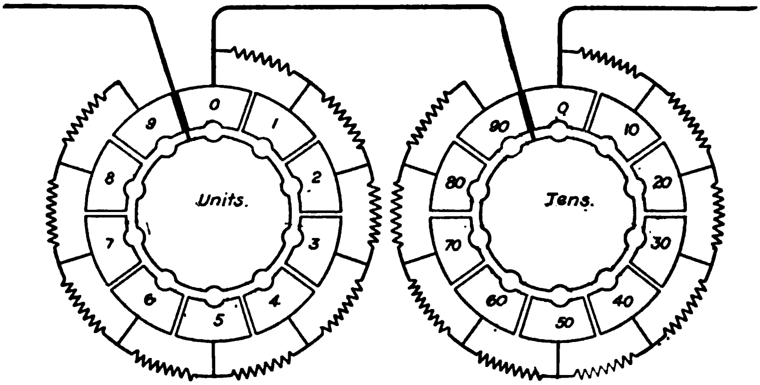

FIG. 68.

The plan calls for a greater number of coils than the "Post-office" one, with a consequent higher manufacturing and selling cost. In spite of this it is now rapidly superseding the old arrangement, as the greater rapidity of working and the higher accuracy of the results attained more than offset the difference.

A portable pattern of the decade type of set is shown in Fig. 69, Fig. 70 giving the wiring connections.

In the latter the block marked "Galv." is so connected that when a plug is inserted between it and the block "Int." the galvanometer indicated in the figure is connected into the bridge network, and used in obtaining a balance in the regular way.

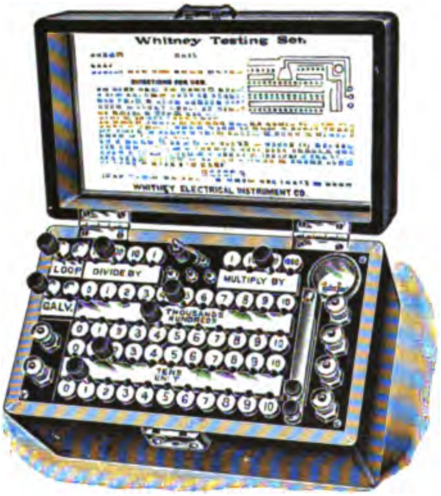

FIG. 69.

When the plug is transferred to the gap between "Galv." and the other block, the gap at *G* is substituted for the galvanometer in the set, and as the gap has binding-post terminals, an outside high sensibility galvanometer may be there attached, and used for more accurate work. The block marked "Loop" is arranged so that when a plug is inserted between it and the block "V&B," the connections of the set are such as to form a regular Wheatstone bridge, the unknown resistance to be measured being inserted at *X*. When the plug is changed to its other position, the connections become those for making the "Murray Loop Test," for the location of faults, as described on page .

Any number of the five cells contained in the box may be utilized by the aid of the connector on the end of the flexible chord coming up through the rubber top between the ratio arms, or that connector may be left free, and an outside source of E.M.F. applied at *B*, whichever the user may desire. The keys *BK* and *GK*, for the battery and galvanometer circuits respectively, are superimposed, so that when the upper one, *BK*, is depressed, first the battery and then the galvanometer circuits are completed, as is the desirable procedure in the general run of tests. The end of the key, *GK*, is extended beyond that of *BK*, however, and provided with a separate button, so that if desired the galvanometer circuit may first be closed. As this set measures

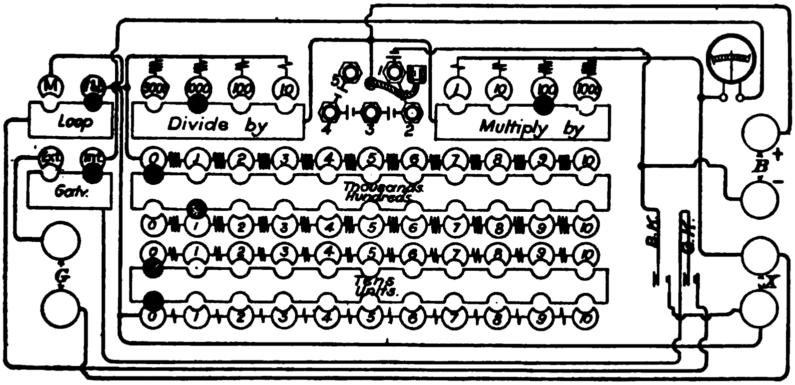

FIG. 70.

but 10 inches by 6 inches by 6½ inches, it evidently forms a convenient, portable device for covering a large range of measurements.

Radial Arm Patterns.

It is possible to dispense entirely with plugs in bridges, by using sliding contacts. In this case the decade system of coils is usually employed, the contacts being arranged in a circle over which sweeps the end of a contact brush. Such bridges are extremely convenient to manipulate, but very careful design and a higher grade of workmanship than for a plug bridge are necessary, as a brush sliding over a flat surface cannot cause the same intimate contact as a taper plug forced into a hole reamed to receive it between two heavy blocks, and variable contact resistances are fatal to accuracy. Crompton & Co. make "dial switch" bridges, as they call this type, with the contacts under plate glass, similar to the scheme used by the same concern in their potentiometer shown in Fig. 56, page 80. The brushes are flat and rather light, and are turned by a hard rubber knob coming up through the glass.

In the Wolff bridges, one of which is shown in Fig. 71, the contact blocks are massive pieces of brass, and the brushes that bear on them are formed of a series of bronze blades fastened to the radial arms that carry them at an angle of 45 degrees. In being moved from one position to another, such brushes automatically wipe the surfaces, and if these are kept slightly moistened with a refined light mineral oil, as directed, they will be found most durable and extremely satisfactory. Tests have been made on such bridges which showed a total resistance of all five sets of brush contacts in series of less than .008 ohms.

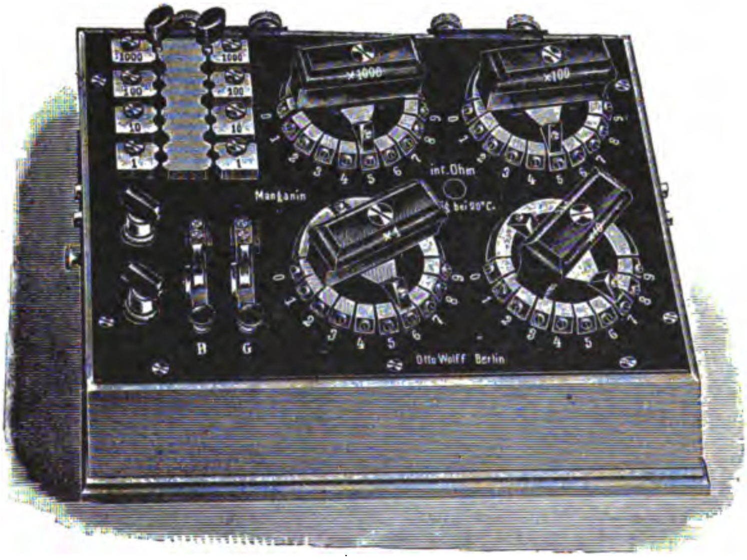

FIG 71.

SLIDE-WIRE BRIDGES.

As was demonstrated on page 95, it is not necessary that the actual values of the resistances of the coils *A* and *B* be known, in order to determine *X* in terms of *C*, but only that their *ratio* be known.

If, therefore, we select a fixed value of C and vary the ratio of A to B, the resistance of X can be determined by application of the formula $X = \frac{BC}{A}$. Devices for resistance measurements in which this variable ratio arm and fixed rheostat arm plan are employed are generall ycalled "slide-wire bridges" and are constructed as follows:

In Fig. 72 MN is a wire having as high a resistance per unit of length as is consistent with mechanical strength, and whose ends are secured to heavy brass or copper bars. A third bar, Q, is provided, gaps being left between its ends and the adjacent terminals just named, the said gaps being designed to be bridged by a standard resistance, C, and the unknown resistance, X, to be measured respectively. Current is put through this network, from a battery whose terminals are attached as shown, and a galvanometer, G, is likewise provided, inserted in a circuit starting from the point, Q, and terminating in the sliding contact, S, which may be moved along the wire, MN. There is, further, a scale beneath MN, that is uniformly divided and serves to measure the distance between the contact and the points of attachment of the bridge wire. It will be observed that the arrangement of the various elements is exactly the same as that of the diagrammatic Wheatstone bridge shown in Fig. 64 and as like parts are similarly lettered, the relationship $X = \frac{BC}{A}$ holds good. In contradistinction to the orthodox Wheatstone bridge, however, in the slide-wire form, the rheostat arm, C, is constant and the ratio of the A and B arms to

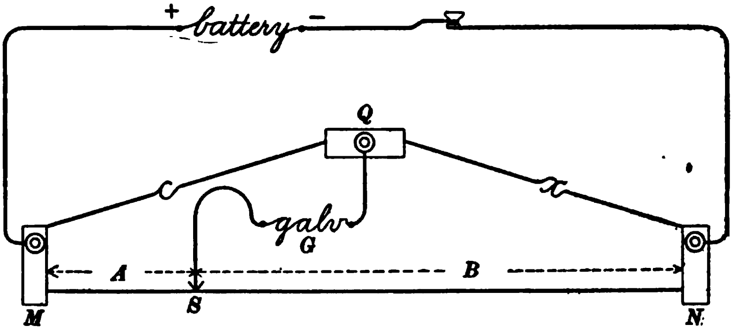

FIG. 72.

one another is varied until a balance is obtained, this being accomplished by sliding *S* along *MN*.

Fig. 72 is simply diagrammatic. In the commercial form of slide-wire bridge there are at least two other air gaps in *O* and *P* that can be bridged over with copper straps when desired, and there is also a wire stretched parallel to the slide wire proper and connected to one terminal of the galvanometer, so that the sliding contact, *S*, makes connection between the two, and the use of a loose wire between *S* and the galvanometer, *G*, is made unnecessary. A slide-wire bridge differing in these particulars from the diagrammatic figure is shown in Fig. 73.

Accurate results are seldom obtained from a single reading with the simple form of slide-wire bridge above mentioned, as not only do errors arise from the fact that the exact position of the contact on the wire may be erroneously indicated by the index attached to the sliding carriage, but the resistance of the straps, *OP*, and the terminal connections incident thereto, all of which, by hypothesis, are supposed to be negligible as compared with the bridge wire, *MN*, may actually be a considerable factor. The errors due to these causes may be eliminated by making two readings in determining the value of a certain resistance, first, by having the arrangement as shown in Fig. 72, and next, by interchanging the *C* and *X* coils. Two different positions of the slide, *S*, on the wire *MN*, are found as a result, and from them the true value of *X* may be determined from the following: If a_1 be the distance from *M* to *S* at the first reading and a_2 that at the second reading, both of the values being

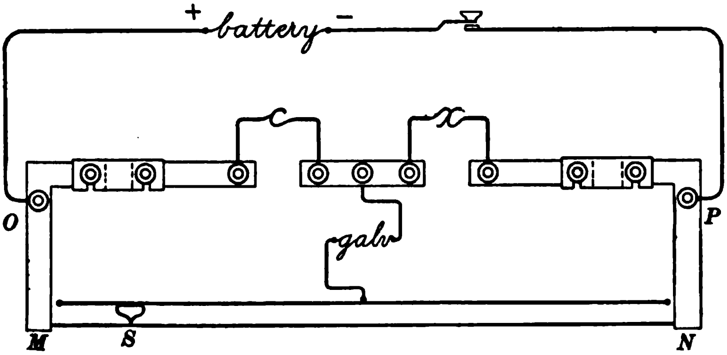

FIG. 73.

expressed in terms of the units of length into which the bridge wire is divided by reference to its accompanying scale, and if n be the total number of units of bridge wire length, we have

$$\frac{X}{C} = \frac{n - a_1 + a_2}{n + a_1 - a_2}.$$

In this equation the resistance of the straps does not enter and the error due to observation of the position of the slider is also absent.*

In the plain form of bridge the length of the bridge wire, MN, is used to cover the whole range of resistance values from zero to infinity, namely, when S is at N, and B is therefore zero, the relationship

$$X = \frac{BC}{A} \text{ becomes } \frac{0C}{A} = 0,$$

and when S is at M, A equals zero, whence

$$X = \frac{BC}{A} = \frac{BC}{0} = \infty.$$

---

* That this is so is evident from the following derivation of the formula (see also Stewart and Gee Physics).

Let y = error due to fact that point of contact of slide on wire is not accurately shown by the position of the mark on the slider carriage relative to the fixed scale.

r_1 = resistance of straps, contacts, etc., from M to C.

r_2 = resistance of straps, contacts, etc., from N to X.

n, a_1 and a_2 having values as before.

Then with coils as in Fig. 73

$$B = n - (a_1 + y) + r_2 \text{ and } A = a_1 + y + r_1,$$

$$\therefore \frac{X}{C} = \frac{B}{A} = \frac{n - a_1 - y + r_2}{a_1 + y + r_1} \qquad (1)$$

when coils X and C are interchanged.

$$A = a_2 + y + r_1 \text{ and } B = n - (a_2 + y) + r_2,$$

$$\frac{X}{C} = \frac{A}{B} = \frac{a_2 + y + r_1}{n - a_2 - y + r_2} \qquad (2)$$

add numerators and denominators of (1) and (2) when

$$\frac{X}{C} = \frac{n + r_2 + r_1 - a_1 + a_2}{n + r_2 + r_1 + a_1 - a_2}$$

$r_2 + r_1$ can be stricken out of both numerator and denominator, as it is a small quantity added to a relatively very large one in both cases, whereupon,

$$\frac{X}{C} = \frac{n - a_1 + a_2}{n + a_1 - a_2}. \qquad Q.E.D.$$

The maximum accuracy of reading is given when *S* is midway between *M* and *N*, that is to say when *A* equals *B*. To increase the length of the bridge wire, *MN*, is not, as a rule, feasible, for if it be made in excess of one meter the apparatus becomes entirely too bulky and difficult both to read and manipulate. The same end, however, can be accomplished electrically by inserting, as is shown in Fig. 74, resistance coils, *H* and *I*. These in effect give a bridge wire whose length, as compared with that of the slide wire alone, is the ratio between the resistance of that slide wire and of that same wire plus the coils *H* and *I*. For example, if the resistance of *MN* were 10 ohms, and in order to obtain the maximum sensibility with the circuit being worked on, resistances were inserted at *H* and *I* each having a resistance of 495 ohms, we would have a total resistance in the ratio arm circuit of the bridge between the points of attachment of the battery terminals of 1,000 ohms; the resistance of *MN* is thus but $\frac{1}{100}$ of the resistance of the ratio arms, and if the scale beneath this wire be divided into 1,000 parts, each unit step of the contact, *S*, on the bridge wire alters the ratio of the length of *B* to *A* by one one-hundredth part of a thousand, instead of one part in a thousand, as was the case before the resistances, *H* and *I*, were inserted. It is largely to render possible the insertion of such resistances that the ordinary slide-wire bridge is built, as illustrated in Fig. 73, with gaps between *N* and *X* and *C* and *M*, respectively. In Fig. 75 is illustrated a slide-wire bridge which has not only gaps for the in-

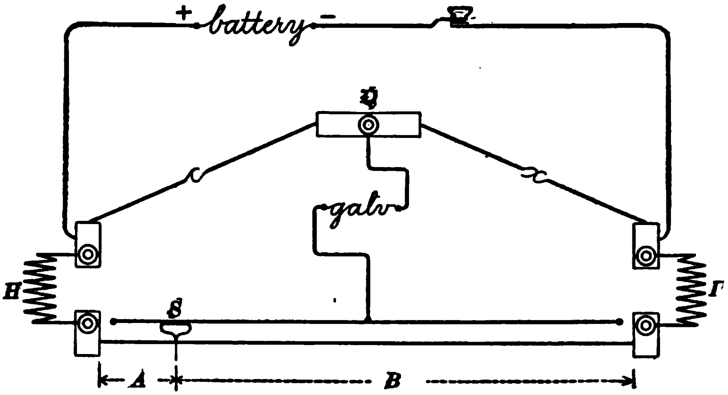

FIG. 74.

sertion of the standard and unknown resistances and for the resistance coils for electrically lengthening the slide wire, but also a mechanical arrangement by means of which the simple shifting of a block carrying bent copper wires reverses the connections of X and C and so, as already explained, enables the errors due to failure to read the bridge wire contact position correctly, and those due to the resistance of the connecting straps to be eliminated.

Ohmmeters.

A commercial form of the slide-wire bridge is the so-called "ohmmeter" shown in Fig. 76. Here the slide wire itself is made up of two lengths, one of them starting at the upper post X and running to the massive square bar at the left, and the other running from the same bar back to the lower right-hand binding-post. The square bar referred to is supposed to be of negligible resistance as compared with the wires, so that the latter may be considered as an electrically single piece which has been doubled back on itself merely for the purpose of getting it into a more convenient form. The source of current is a set of dry cells secured inside of the case, and a telephone receiver is used as a galvanometer, it having the advantages for that purpose mentioned on page 63. The battery circuit key is built into the telephone receiver, so that the same hand that holds the latter can manipulate the battery circuit. The stylus shown as lying on the top of the hard rubber bar that extends lengthwise of the set is connected in the receiver circuit, and serves both as the key for that circuit when it is tapped on the wire and as an index for indicating the point on the scale where balance is obtained. There are four standard resistance coils, usually of 1,

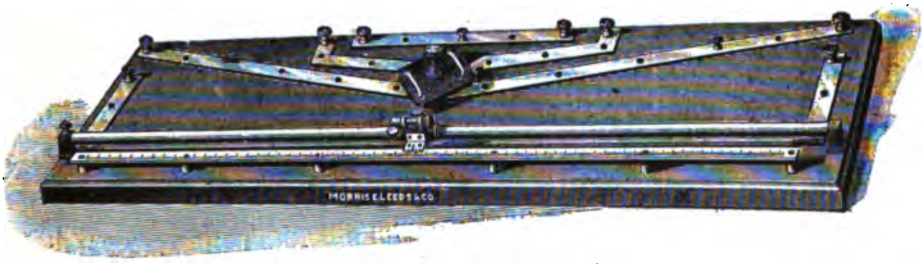
MORRIS E. LEEDS & CO.

FIG. 75.

10, 100, and 1,000 ohms value, any one of which may be used as the "C" arm of the bridge by inserting the single plug shown in an appropriate socket. The sockets are labeled "brown," "blue," "red," and "black," and there are four sets of numerals on the scale printed in these respective colors, the purpose being to make it difficult for even an unskilled observer to make any mistakes in results, as when the plug is in the hole labeled "brown," the brown numerals are to be read, when in the hole labeled "blue," the blue numerals, etc. There is no necessity of making any computation when measuring resistance with this bridge, as the scales, instead of being equally divided, are marked off directly in ohms. That this is possible is evident from the following: Using the notation of Fig. 77, which shows diagrammatically the connections of the ohmmeter, it is clear from the law of the Wheatstone bridge that

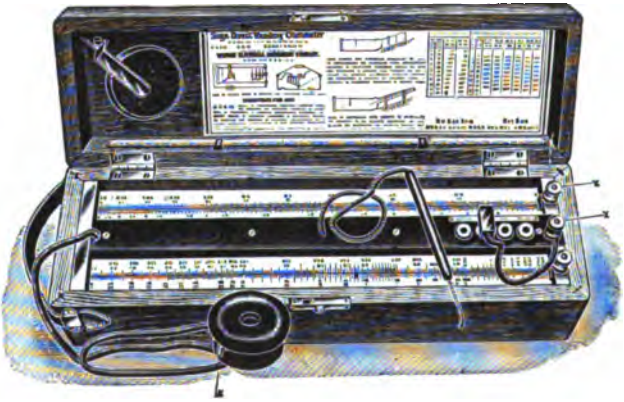

FIG. 76.

$$A : B :: C : X.$$

Now $A+B$ is the total length of the doubled-up wire, which in the actual instrument is $30''$, hence, $B = 30'' - A$. C, the standard coil, has a resistance of say 1 ohm. The formula then becomes,

$$\frac{A}{30'' - A} = \frac{1}{X}, \quad \text{or} \quad X = \frac{30'' - A}{A},$$

or in other words, for each value of X, there is a single corresponding value of A, which may thus be marked on the scale.

If C be made 10 ohms, the value of X is evidently multiplied by ten also, that is to say, the values of the scale readings are multiplied by ten. The same, of course, applies to other values of the C coil.

THE VARLEY BRIDGE.

It can be shown that in measuring high resistances with a Wheatstone bridge or with a slide-wire bridge it is desirable to have the resistance of the A and B bridge arms (see Fig. 64), or of the slide wire as a whole, high also. This is not feasible with the ordinary slide-wire bridge or the ohmmeter just described; for if, using suitable commercial alloys, a total resistance of about 15 ohms for the slide wire be exceeded, the diameter of the wire becomes too small to be strong mechanically, or to withstand the wear of the contact devices without introducing appreciable errors due to the destruction of the uniformity of the resistance of the wire throughout its length. The simple expedient of increasing the geometrical length of the wire cannot be far extended, because, as already explained, this makes the apparatus too bulky. It is, however, possible to lengthen the wire electrically without spreading it over a greater length, this being accomplished by forming it of a set of coils of wire of like resistance, all connected in series and each provided with terminal buttons with

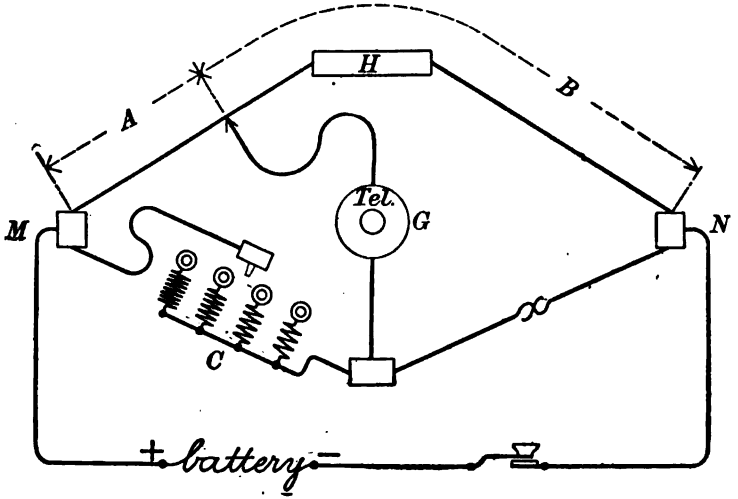

FIG. 77.

which the device corresponding to the slide-wire contact makes connection. An arrangement of this simple kind is shown in Fig. 78, in which if each of the 10 coils have a resistance of 1,000 ohms we have the exact equivalent electrically of a slide wire having a resistance of 10,000 ohms, but contact with it can be made only at ten equidistant points. Ten steps in the bridge-wire resistances evidently fail to provide means for making close adjustment; in fact, it should be possible to have 1,000 steps to equal the plain slide-wire bridge, the position of whose contact can almost invariably be read to that fraction of its length. It is, of course, out of the question, on the score of price and bulk, to make the apparatus contain 1,000 coils each of 1,000 ohms resistance, but the same end may be accomplished by using the electrical vernier described in connection with the potentiometer on page 82, which plan for the potentiometer was copied from the bridge, as devised by Varley. The elementary Varley bridge is diagrammatically shown in Fig. 79, and consists of a series of 11 coils each of 1,000 ohms resistance, and of 10 coils each of 20 ohms resistance, connected in series, and with the terminals of the latter series held with a fixed distance between them by a carriage movable along the contact buttons attached to the 1,000 ohm coils. From the potentiometer description it can readily be seen that, using the two terminals attached to the 20 ohm coils and the galvanometer terminal sliding on the contact buttons of the 20 ohm coils, the device is capable of inserting in the galvanometer circuit between the point *M* and the connection running to the galvanometer, resistances between zero and 10,000 ohms, in

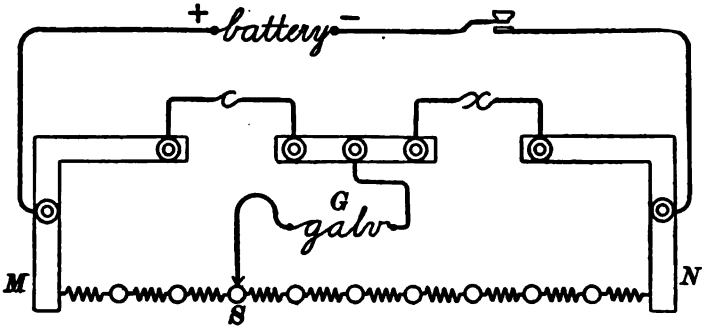

FIG. 78.

steps of 10 ohms each, or in other words, by steps of one one-hundredth at a time.

As at least 1,000 steps are needed for accurate work, the commercial form of Varley bridge, commonly termed the "Thompson Varley slide," is built with 101 coils of 1,000 ohms each, and 100 vernier coils of 20 ohms each. The coils are in separate boxes with the contact buttons arranged in circles, as shown by the illustration of the device, Fig. 80, and the contact arms are pivoted in the center of these circles. Connections are made as in Fig. 81. Readings can be taken to one part in ten thousand, there being that many steps available, namely, one hundred variations on each of the one hundred positions of the double arm.

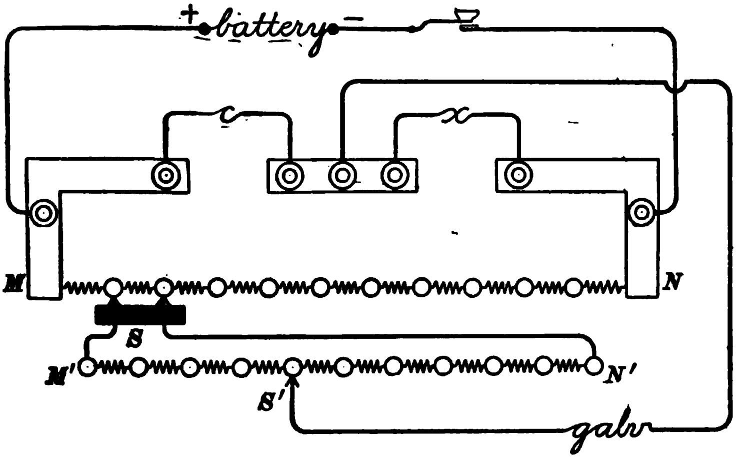

FIG 79.

The high resistance of the coils entering into the construction of this Varley slide make the accuracy very high, but the number of the coils is, on the other hand, high also, and the resultant cost prohibits its use in many cases.

The electric vernier principle may be employed to make a cheaper slide with fewer coils but the same number of steps by simply extending it further, putting a slide on a slide. Each added group of ten slide coils multiplies the possible number of steps by ten, but on the other hand adds one more to the number of contact arms that must be adjusted to get the balance.

An instrument in which this slide on slide plan has been carried to an extreme is the Cushman bridge, where there are five sets of coils, which, theoretically, would enable the comparison of two nearly equal resistances to an accuracy of .0002 per cent. In practise, however, such refinement is as absurd as the array of figures after a decimal point that is often indulged in in figuring the horse-power of an engine, from indicator cards, as the errors due to slight differences in coil resistances, to the contacts, to temperature, etc., amount to many times this percentage.

VOLT AND AMMETER METHODS.

From Ohm's law it is clear that if the current passing through a resistance be measured and the difference of potential between the terminals of the resistance simultaneously noted, the value of the resistance can at once be figured, by dividing the value of the latter observation by the former. This method of resistance measurement is one of somewhat limited application as regards the range of resistance that it can cover; for, where the resistance is high, the current through it must usually be kept

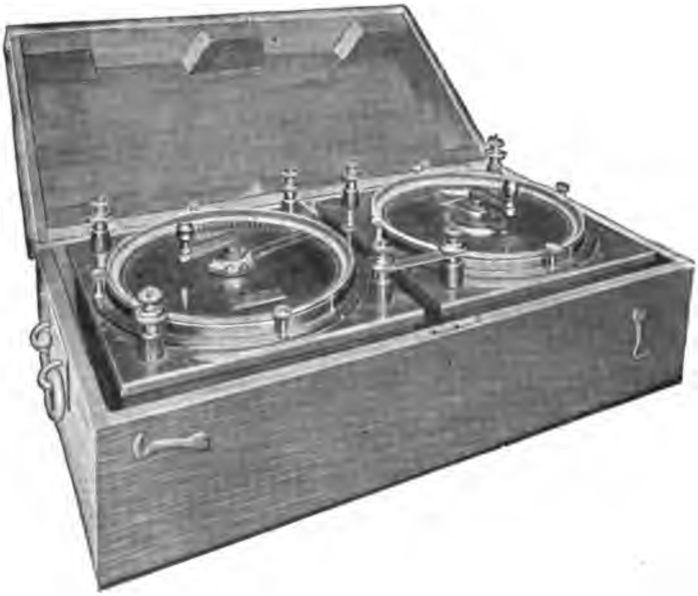

FIG. 80.

of a very low amperage in order to avoid heating errors or actual burning out, and instruments for the measurement of very low amperage, having but limited application, are but seldom on hand; if, on the other hand, the resistance be low, the current required to cause a closely measurable drop becomes correspondingly high, and it is not always convenient to procure a source of such heavy current, or an instrument for measuring it. It should be noted that unless the potential-measuring instrument is one that consumes no current, namely, is of practically infinite resistance, as in the case of the electrostatic device, errors are introduced. Referring to Fig. 82, if *W* be the resistance, *A* the current measuring instrument, *V* the potential measuring instrument, and *B* the source of current; while the meter, *V*, indicates the true potential difference at the terminals

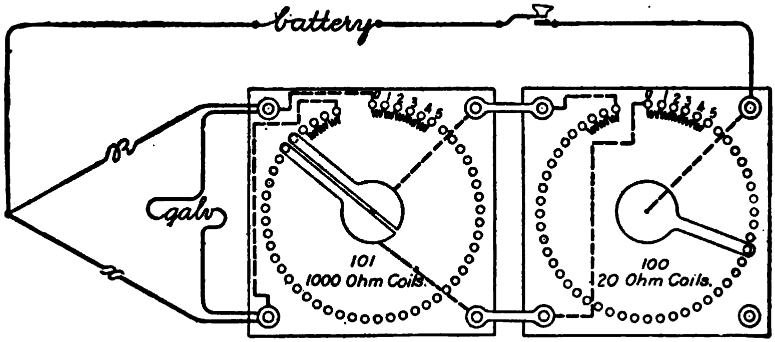

FIG. 81.

of *W*, if it be in calibration; *A* gives, not the current through *W* alone, but through the circuit formed by *W* as shunted by the resistance of the instrument, *V*. If the only other possible scheme of connection be used, as shown in Fig. 83, the state of affairs is reversed, for while *A* now shows only the current flowing through *W*, *V* indicates the drop due to the flow of that current, not only through that resistance, but also that of the instrument *A*.

That these errors are by no means inconsiderable will be evident from the following examples: Take first the connections shown in Fig. 82. Let the range of the voltmeter, *V*, be 1 volt and its resistance 100 ohms, the range of the ammeter *A* be 1 ampere and its resistance .05 ohms, and the true value of the resistance *W* be 1 ohm.

Adjust the current from the battery *B* by a rheostat, or other convenient means, until the ammeter shows exactly 1 ampere. The voltmeter *V* will then show, not 1 volt, as would be necessary in order that the solution of Ohm's equation should give a value of *W* of 1 ohm, but .99 volt, because the resistance of the circuit formed by the resistance *W* shunted by the voltmeter is, from the law of divided circuits, $\frac{100 \times 1}{100 + 1} = .99$ ohms (nearly) and the drop in potential across the terminals with one ampere flowing would be .99 volts. Neglect to take into consideration the finite value of the resistance of the voltmeter would therefore cause an error of 1 per cent in the calculated result. Take now the connections, as in Fig. 83, the other conditions remaining as before. The voltmeter *V* would now show 1.05 volts, as this is the drop across the terminals of a circuit of 1.05 ohms resistance with 1 ampere flowing, and the calculated value of *W* would hence be 1.05 ohms instead of its true value of 1 ohm, which is an error of 5 per cent. It will thus be seen that, unless the measurements are to be of the roughest, due allowance must always be made for the resistance of the instruments.

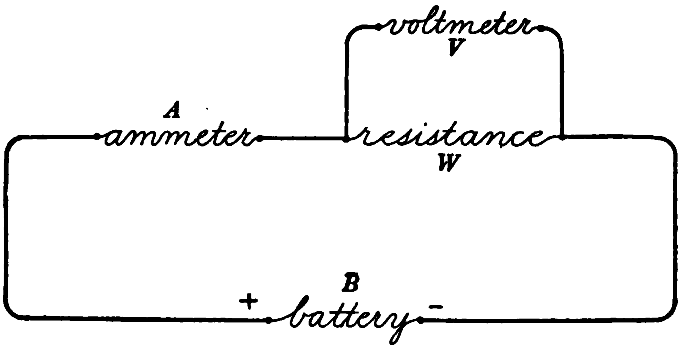

FIG. 82.

MEASUREMENT OF LOW RESISTANCES.

The Wheatstone and slide-wire bridges are not suitable for measuring low resistances, that is to say, those having a value of .1 ohm or under, as the resistance that these devices measure is the *total* resistance between the junction of the *B* and *C* arms (see Fig. 64) with X, and include, not only X itself, but the leads used to make connection between X and the bridge, and of all of the contacts in that circuit. The resistance of the leads is nearly constant, but their value may be so large, as compared with that of the resistance under test, that a very small error in the measurement of the total would be an exceedingly large percentage of the value of the unknown resistance, and hence the test entirely unsatisfactory.

The resistances of the contacts are not even constant, as these depend on the pressure between them, the condition of the surfaces, and their area. They may easily vary some thousandths of an ohm in value, even under favorable circumstances, and with a value of H as high as .1 ohm, each thousandth would represent 1 per cent.

It is evident, therefore, that for the measurement of low resistances methods should be employed in which the resistance of the leads and contacts does not enter into the results.

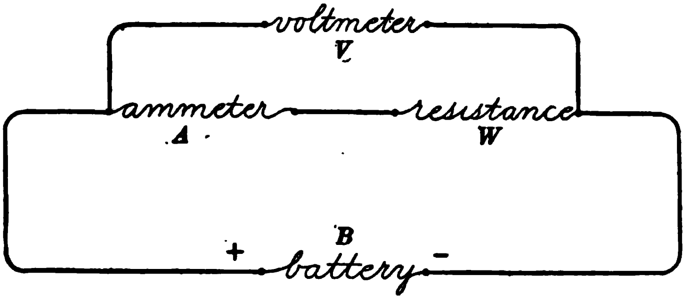

FIG. 83.

KIRCHHOFF BRIDGE.

The earliest device of this type seems to have been the Kirchhoff bridge, a device that was probably due to Heaviside, who described it in the early seventies. The instrument used in this method is a differential galvanometer ("Galv.," Fig. 84) and the low resistance X to be measured is connected in series with the standard resistance, S, the current flowing through both being taken from a source, B, capable of supplying considerable current. The resistance of the standard, S, between two points, A and C, must be accurately known, and the bar of metal forming it must be divided between these points into as many equal resistance steps (often one hundred) as possible, by appropriate markings. Contacts *M* and *N* make contact with the standard bar *S*, and the similar contacts *P* and *Q* make connection at the ends of the unknown bar.

The electrical connections are so made by the contacts that the current through the coil of the differential galvanometer due to the difference of potential between the points *M* and *N* tends to cause a deflection opposite to that which would be given by the current through the other coil, due to the difference of potential between *Q* and *P*. *N*, *Q*, and *P* being fixed, *M* is moved along *S* until the galvanometer shows no deflection. The resistance of the bar, *X*, between the points *Q* and *P* is then, from Ohm's law, the resistance of that part of the bar, *S*, included between *M* and *N*, for the same current flows through both, as they are connected in series, and the drops in potential are alike, as the galvanometer shows no deflection. The resistance of the battery leads, of the wire joining the two resistances and at the points of contact of these with the bars, do not enter, as they are not in the measuring circuit and merely affect the current strength. The resistance between the contacts, *M*, *N*, *Q*, and *P*, and their resistance bars, do not enter either, as they are negligible in comparison with the high resistance of the galvanometer.

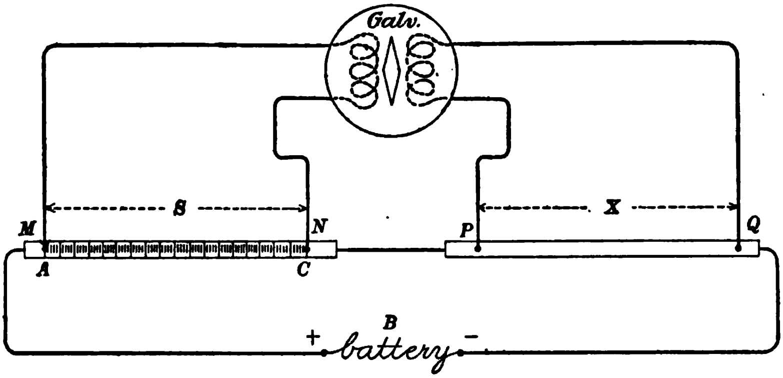

FIG. 84.

As the accuracy of results obtained by this method depends on having a galvanometer that is truly differential, the instrument should be tested for that quality before use. To do so, connect the two coils in series, but in opposition, and pass a very weak current through them, whereupon there should be no deflection. The coils should then be coupled in opposition but in parallel, and current again applied; if there is still no deflection, the coil resistances are alike. The latter test is the one actually determining the fitness of the apparatus for use in making this test, as while if it shows no deflection the instrument may still not be truly differential, any error due to that cause is offset by a difference in coil resistances.

The galvanometer should also be tested to see that its two coils are insulated from one another so that no current can flow between them.

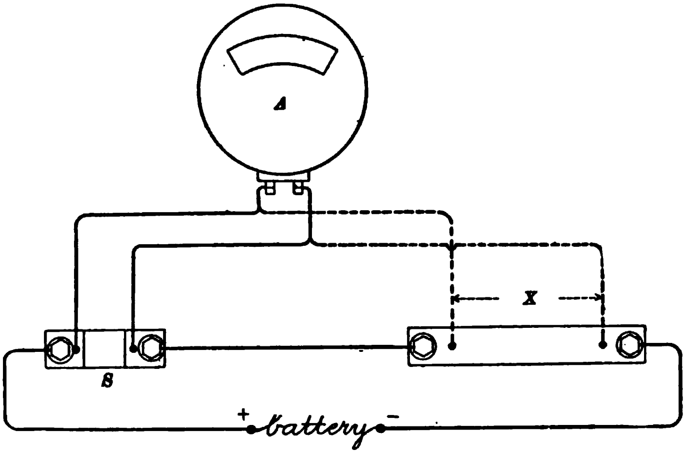

FIG. 85.

MEASUREMENTS WITH AN AMMETER.

Low resistances of nearly the same value can be measured with the aid of commercial ammeters of the type in which the shunts are separate from the instruments themselves, provided that the resistance of their shunts is known. For instance, referring to Fig. 85, *A* represents the ammeter, *S* its shunt, *X* the unknown resistance, and *B* the source of current. The same current flows through *S* and *X*, as they are connected in series; and if the ammeter *A* be one in which the angular deflections of the needle are proportional to the current strengths, or even if this be not so and the scale be divided so as to indicate current strength, *X* may be found in terms of *S*, from the fact that, as will be evident on consideration, the drop across *S* is to the drop across *X* as the resistance of *S* is to the resistance of *X*. For instance, if the current through *S* gives a deflection of ten scale divisions on the instrument, *A*, and that across *X*, when the terminals of the instrument are shifted to take up the position shown by the dotted lines be twenty scale divisions, then *X* is twenty tenths, or two times *S*. A few manufacturers make the drop of all of their shunts uniform, for instance, 50 millivolts when worked at maximum load. From this data the resistance of the shunt between the points at which the connection to the instrument is made is easily figured; that of a 100 amperes hunt on the 50 millivolt basis being .005 ohms, and that of a 1,000 ampere shunt .0005 ohms, etc. If in this example the current strength supplied by *B* be such that the instrument, *A*, gives a reading of ten scale divisions when its terminals are attached to a shunt of 100 amperes capacity, *S*, a resistance, *X*, in series with *S*, the drop across which causes one scale division deflection, will have a value of .0005 ohms, or generally, if the resistance, *X*, give *N* scale divisions deflection, it has a value of .0005 *N* ohms. The resistance of *A* is usually sufficiently high so that the resistance of the contacts between its leads and the *S* and *X* resistances is negligible, and such work as measuring the resistance of armature coils can therefore be rapidly and accurately conducted with inexpensive apparatus.

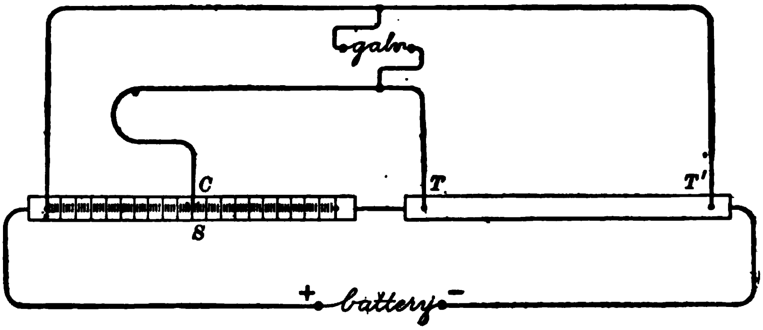

FIG. 86.

THE THOMSON DOUBLE BRIDGE.

The Kirchhoff bridge necessitates the use of a differential galvanometer, and this instrument is not often available. Lord Kelvin devised a modification of this bridge, which renders it possible to use an ordinary galvanometer, the connections being as shown in Fig. 86. The leads from the standard and unknown resistances are, as is seen from the figure, connected, so that the E.M.F.'s at their terminals are opposed, and when these are equal the galvanometer of course gives no deflection. The standard bar *S* is divided up, so that fractions of its length, and hence resistance, may be read off, as in the Kirchhoff bridge; and when the sliding contact, *C*, which is adjustable along its length, reaches the point where the galvanometer gives no deflection, the resistance between the fixed terminal and the movable one is evidently that between the terminals, *T* and *T'*, of the resistance to be measured. In the actual Kelvin, or as it is still more generally known, the Thomson double bridge, there are inserted in the leads between the galvanometer and the standard and unknown resistances, resistance boxes, the value of whose resistance may be varied by withdrawing the plugs, as is shown in Fig. 87. If the resistance of *P* be made equal to *R*, and that of *A* to *C*, the resistance of the unknown bar, *X*, is read off directly from the standard bar, as above outlined. If, however, the ratio of *R* to *P* be made, for instance, ten, and that of *C* to *A* ten, the resistance of *X* is ten times

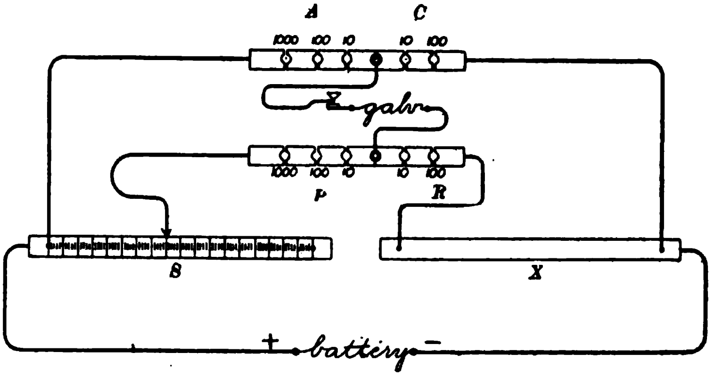

FIG. 87.

that of *S*, and *vice versa* when the ratios are interchanged, just as in the case of the ratio arm coils in the Wheatstone bridge.

A commercial form of the Thomson double bridge suitable for measuring resistances ranging from 1 ohm down to .000001 ohm (1 micro-ohm), and termed a "micro-ohmmeter," is illustrated in Fig. 88, the connections being as shown in Fig. 89. In this instrument the standard resistance is a calibrated platinum silver alloy bar having a resistance of .01 ohm between the points designated by zero and 100 on the scale placed parallel to it. With the aid of suitable terminals, the unknown resistance is placed in series with this and a battery, and a movable contact, *M*, is slid along the standard until the galvanometer, which is built into and forms part of the apparatus, no longer shows a deflection. If the resistances of the ratio arm coils then have a ratio of unity, the resistance of the unknown bar is read off directly. Varying ratios of the resistance of the ratio arm coils are obtained by sliding the carriage *C* along its guides, in this way giving the apparatus a range of from one hundred times that of the maximum resistance of the standard bar, that is to say 1 ohm, to one one-hundredth of the minimum resistance readable on the standard bar, that is to say 1 micro-ohm. The numerals 2, 3, 4, 5, and 6, that are displayed through the opening in the carriage *C* when resting on different contacts, show the number of decimal points to be stepped off in

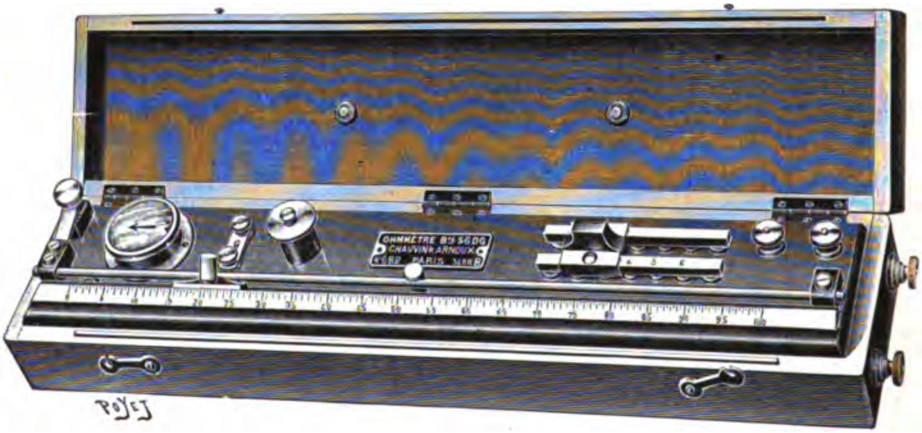

FIG. 88.

noting down the readings. If, for instance, the galvanometer be brought to a position of zero deflection when the movable contact, *M*, stands at the scale division numbered 44, the resistance of *X* is .44 ohms, if the numeral 2, indicating two decimal places to be stepped off, be visible through the opening in *C*. If the numeral 5 were visible through the said opening at the time, five decimal points would have to be stepped off, and the resistance of *X* would be .00044 ohm. A strap, *G*, connecting two binding posts at the top of the instrument, is provided, and when it is removed a sensitive reflecting galvanometer may be inserted when it is desired to make determinations of a high degree of accuracy.

As in all Thomson double bridge measurements, this apparatus gives results that are independent of the resistance of the leads running from the unknown bar to the instrument and of the contacts between it and the lead terminals, for these are negligible in comparison with the resistance of the galvanometer and the ratio arm coils. As the method is a zero one, in which determinations are made when no current is flowing through the galvanometer, it is independent of variation in the sensibility of this also. The complete apparatus is inclosed in a small, light carrying-case, and the storage battery that is sometimes supplied with the equipment is likewise compact and light, so that we have a truly portable device for the measurement of very low resistances. The method of operation is so simple that reliable results may be obtained when placed in the hands of an unskilled workman.

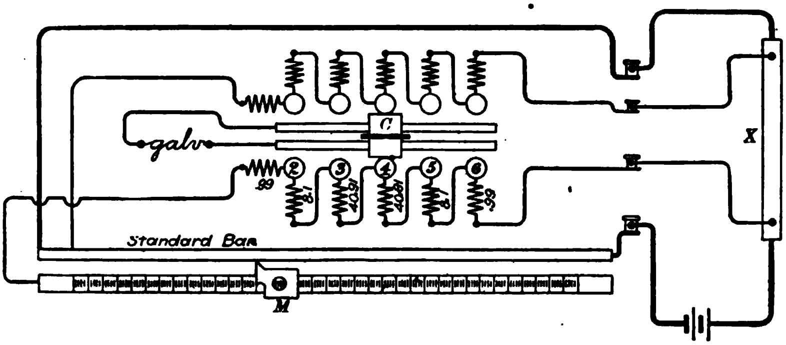

FIG. 89.

THE CAREY–FOSTER METHOD.

The slide-wire bridge may be used to determine with a high degree of accuracy the difference in resistance between two coils of nearly equal value. To accomplish this a balance is first obtained with the standard and unknown coils connected in the bridge circuit, as shown at *S* and *X*, Fig. 90, respectively, and then the second determination is made with *S* and *X* interchanged. The bridge wire reading in the latter case will be different from that in the former, and the resistance of the bridge wire included between the points where contact was made when the balances were attained is the difference in resistance between *S* and *X*. This, of course, makes it necessary that the resistance per unit of length of the bridge wire be known, and this is something that can be determined in several ways. If, for instance, we have two coils, whose resistances differ by a known amount, the resistance per unit length of slide wire can be obtained directly from the above relationship, the unknown value then being that of the bridge wire, whereas the *S* and *X* in the formula are known. Another method is similar to that used in determining the uniformity of the drop along a potentiometer wire, as mentioned on p. 76. Even if we have but a single standard resistance, having a value of say 1 ohm, we can make up an exact duplicate of it of any resistance wire, and then shunt one of the two by a known resistance of considerably higher value, say 100 ohms. The ratio of the shunted resistance to the unshunted standard one is now $\frac{100}{100+1} = .9901$ to one, which gives us a means of calibrating the bridge wire in steps of .0099 ohm each.

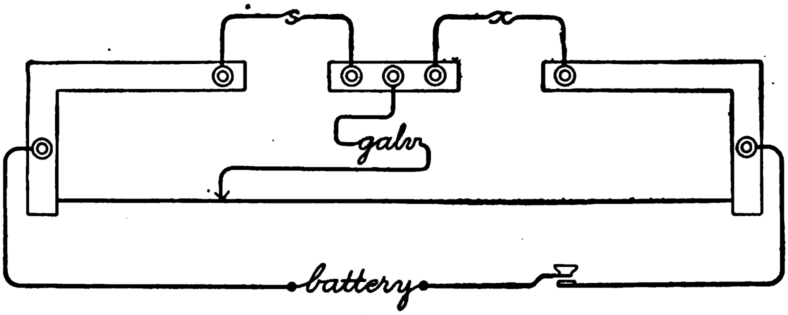

FIG. 90.

As the bridge wire may be made of a large diameter to advantage, a long length represents only a small resistance, so that two resistances of nearly equal value may be compared very accurately. This method is so delicate that it becomes probably the most valuable one for use in determining the temperature coefficient of metals, the one portion of the specimen being maintained at a uniform normal value by immersion in an oil bath, and that of the section from which the temperature coefficient is to be determined immersed in a similar bath whose temperature can be varied as desired. If the two sections be first adjusted to have the same resistance at the same temperature, and one be then raised to some new temperature, the resistance of the wire between the balancing points on the bridge wire is the increase in resistance due to that temperature change. By making a series of determinations in this way, the curve showing the relation between the temperature and resistance of any given specimen of conductor may be drawn.

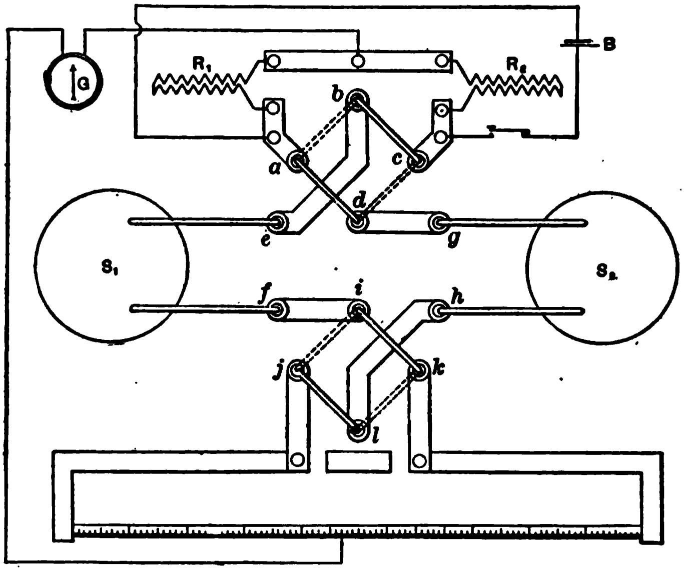

FIG. 91.

Since, in order that the temperature may be properly controlled and accurately measured, it is necessary that each specimen be immersed in a bath of oil, which is constantly stirred, it is advantageous to provide some means of interchanging the coils electrically instead of mechanically, in order to avoid moving them about by hand. The regular slide-wire bridge can be made to answer these requirements if the connections thereon be arranged as shown in Fig. 91, the double circles in this figure indicating mercury cups. The apparatus for electrically interchanging the position of the coils consists of a pair of hard rubber squares drilled near the corners to receive U-shaped pieces of heavy copper wire carefully amalgamated at their ends and supported only loosely by the framework, so that their weight acting downward makes a good contact between their lower faces and the bottom of the mercury cups in the bridge. When this apparatus is placed so that the copper connectors *ad*, *bc*, *ik*, and *jl* have the positions shown in the figure, the connection of the standard coil is in the gap in the bridge opposite to that which it occupies when the blocks have been lifted and rotated 90 degrees about a vertical axis.

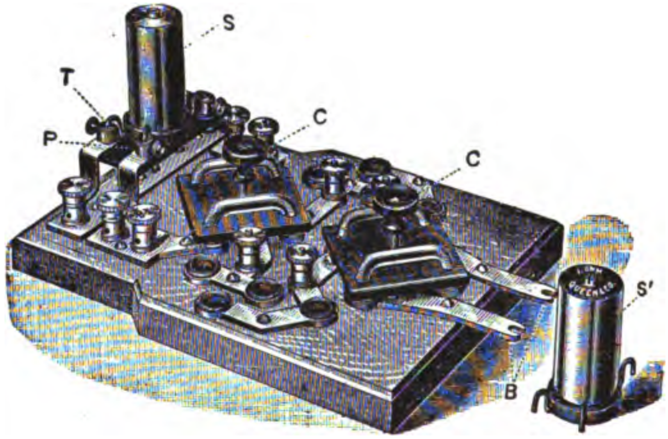

FIG. 92.

For slide-wire bridges not supplied with connections and terminals for the use of the reversing commutator just described, a separate commutator is often used, one of these being shown in Fig. 92.

A compact Carey-Foster bridge and commutator combined is shown in Fig. 93, the plan view being given above the perspective one. The bridge wire is very short in this piece of apparatus, and protected from radiation by a hard rubber strip, so that there is little probability of error due to thermal E.M.F's. By means of shunts, one of which is shown detached and placed alongside of the apparatus, the value of the bridge wire may be varied as desired. The commutating device is double, and when manipulated by raising and turning the upper knurled hard rubber button exchanges the resistance coils and battery connections simultaneously; whereas when the lower button alone is raised and given a quarter of a revolution, the battery connections alone are reversed.

CONDUCTIVITY BRIDGES.

For the rapid commercial measurement and comparison of low resistances, such as the measurement of the conductivity of samples of large copper wires, a modified form of Carey-Foster bridge, known as the conductivity bridge, is often employed. The diagram of the connections in this device is given in Fig. 94, a perspective view of the complete apparatus being given in Fig. 95.

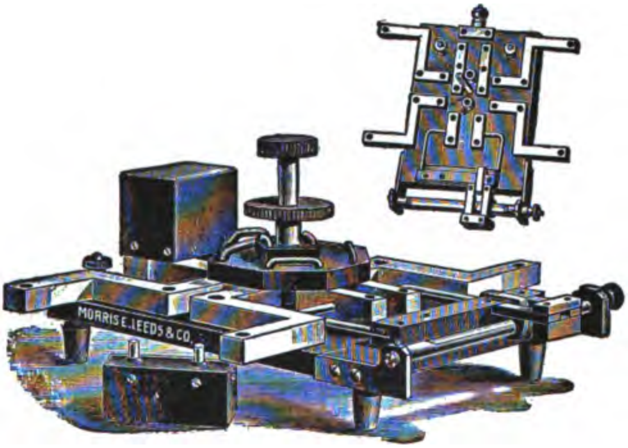
MORRIS E. LEEDS & CO.

FIG. 93.

The method of operation is as follows: In the figure *C C′* is the bar under test, the same being secured in place by the heavy clamps shown; A and A′ are ratio coils of equal value, usually wound together so that they will always be at the same temperature; and S_1 and S_2 are two resistances made of material having the same temperature coefficient as the specimen under test; *R* is a separate resistance that may be used to shunt either S_1 or S_2, thereby changing the resistance of either by a known amount.

In taking a reading, the coil *R* is placed as shown in the figure, and the sliding contact *G* is moved along the test bar until the galvanometer shows no deflection.

R is then changed over to shunt S_1, and a new point on the bar at which *G* rests without causing a galvanometer deflection is found. The resistance of the length of the bar measured between the two balance points is, as is evident from the description of the Carey-Foster method, the difference between the resistance of either of the like coils S_1 or S_2 alone, and when the same is shunted by *R*. Means are provided so that *R* may be shifted from one position to another without opening the protective casing.

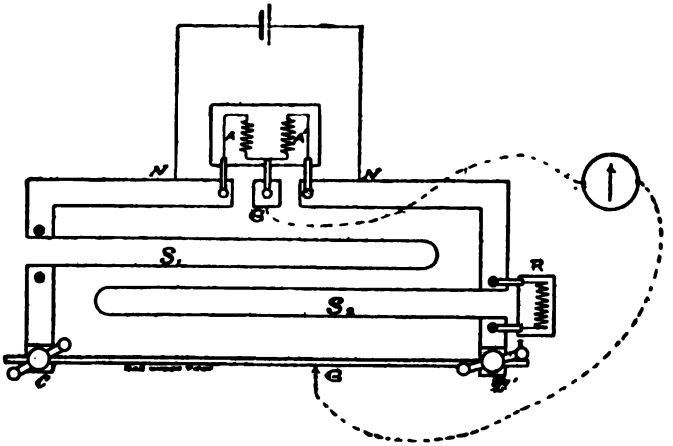

FIG. 94.

THE MATTHIESSEN AND HOCKIN BRIDGE.

The Matthiessen and Hockin method of measuring low resistances consists in connecting up a standard low resistance, the unknown one, a straight resistance wire whose resistance per unit of length has been determined, and the source of current, all as shown in Fig. 96. A galvanometer has its terminals attached to separate contacts; the upper one of which can be used to make contact between the extremities of the standard bar, *S*, and the unknown resistance, *X*; the lower one being movable along the stretched wire, which latter is often the wire of an ordinary slide-wire bridge. The upper galvanometer terminal being placed at the left-hand extremity of the bar, *S*, the lower one can be moved along the slide wire until a point is reached where the galvanometer no longer shows deflection. The potential at this point, *A*, is then the same as the potential at the end of the standard bar. The upper terminal is then moved to the other end of the standard bar, and the lower one slid along the slide wire until the galvanometer again shows no current. This second balance point is lettered *B* in the figure. In a similar way, the points *C* and *D* are found on the slide wire at which the potentials are the same as the potentials at the ends of the unknown resistance. The value of *X* may then be calculated directly from the relation,

$$\frac{S}{X} = \frac{AB}{CD}.$$

RAIL BOND RESISTANCES.

In the ordinary electric trolley system, the current led to the car through the overhead trolley wire is returned, after passing through the motors, by the tracks, which have fish-plates to form the mechanical union between rail ends and "bonds" consisting of more or less flexible electrical conductors secured to each rail end to make the electrical union. As the number of rail joints is large in even a small system, it is important that the bonds bridging them shall make good contact, as otherwise there will be a considerable useless expenditure of electrical energy in forcing the current through. It is seldom possible to inspect the bonds visually in order to determine whether or not they are still firmly attached to the rail ends, and, even if it were, a rigid mechanical connection is not necessarily a good electrical one.

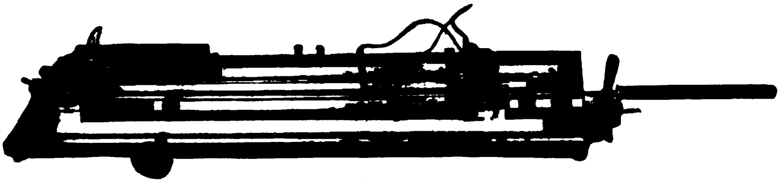

FIG. 95.

It is, as a rule, impossible to measure the resistances of a bond by passing a known current through it and observing the drop across it, as cars that are in operation cause a constantly varying, and, of course, unknown, current to flow. Practical devices for the measurement of bond resistances utilize the varying current normally flowing through the rail and bond, and take advantage of the fact that, however the current and the consequent drops across the resistance offered by the bond and that offered by a standard length of rail vary, the ratio of these drops to one another remains constant.

In the Conant bond tester, the drops are taken by means of three chisel-ended pikes which are struck into the rail faces by the operator and his assistant. The drop of potential across the bond between one pike and the center one is compared with the drop over a length of solid rail measured between the center pike and the remaining one by means of a device suspended from the observer's shoulders. The instrument consists of a box containing clockwork-driven interrupter which periodically makes and breaks the circuits. The latter are connected in opposition electrically, and hence, if the resistance of the bond and of the length of solid rail included between the contact points are alike, no current will flow, and the telephone receiver that the observer has at his ear will emit no sound. If the receiver does "click," the assistant moves his chisel along until silence ensues, whereupon the bond resistance is known to be the same as that of the length of rail between his contact and the center one.

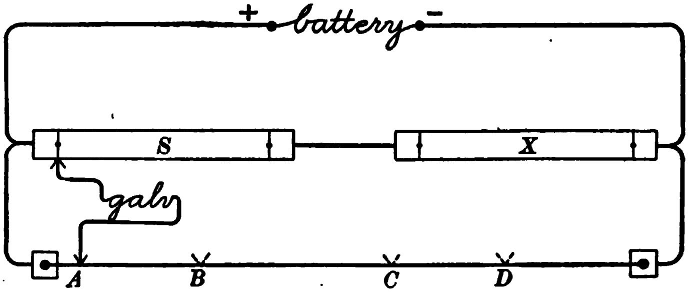

FIG. 96.

Two other forms of bond testers are shown in Figs. 98 and 99 respectively.

In the first, three contact points are carried by a bar of springy, non-conducting material so arranged that they scrape a bright surface for themselves when being placed in position. The center contact is independently spring-supported, so as to insure contact of all three points even if the rails should be worn and the surfaces not in the same plane. The drops due to the passage of the regular line current through the standard length of rail *B C* and the bond *B A* respectively, are indicated by a pair of millivoltmeters that are electrically connected to the points of contact by suitable leads. The two millivoltmeters are built on one base for convenience in transportation and in making observations; and the one that is used to measure the drop across the bond terminals is made with two ranges; one high one, normally in circuit, and intended to prevent the instrument from burning out should the bond be broken and the E.M.F. across it consequently very high, the other for obtaining an accurate reading of the drop after the first reading shows it to be within the capacity of the more sensitive scale. The change from the low sensibility to the high one is effected by depressing a spring-controlled button conveniently located at the side of the instrument. The millivoltmeter for taking the drop on the standard length of rail is a plain single-scale instrument. After taking a reading, the resistance of the bond may be figured, if desired, from the obvious fact that the resistance of the bond is to the resistance of the standard length of rail as the drop across the bond is to the drop across the standard length of rail. The double millivolt-

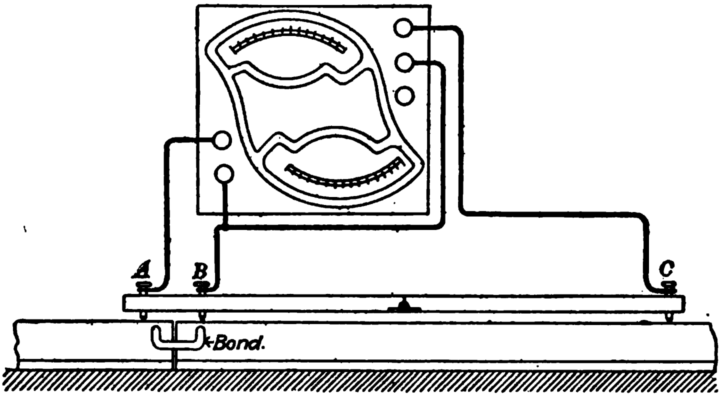

FIG. 98.

meter is usually used mounted on a tripod for the sake of having a steady foundation, but it may be used suspended from the observer's neck, if desired. This form of bond tester is convenient in that it may also be used as a direct current ammeter if a suitable shunt be supplied for use with the millivolt scale, and as a direct current voltmeter if a suitable multiplier be supplied for use with the volt scale. It is also convenient for making the so-called "bar to bar" test on armatures, in which case one of the two millivoltmeter movements may

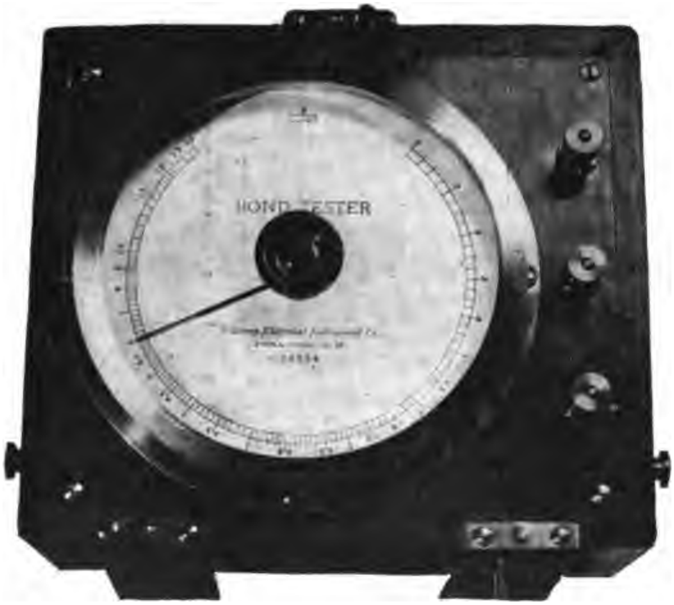

FIG. 99.

be used to show the drop across the individual commutator segments; the other, being used to make sure that the test current strength remains constant, by connecting it in shunt to the wire through which that current is passing.

The second form of bond tester is a direct reading instrument, showing directly on a scale the resistance of the bond under test in terms of the number of feet of rail length having an equivalent resistance, but it cannot be used as a voltmeter or ammeter. An illustration of the instrument itself is given in Fig. 99; the instrument in use is shown in Fig. 100. Contact with the rail is made with a contact bar like that used with the apparatus described above, the contact pieces themselves being short sections of hack saw blades, which have hard, sharp points, and are easily and cheaply renewed when dulled.

The bar has an upright at its center, so that the observer may manipulate it conveniently. The bond tester proper is a modified bridge which uses the standard rail length as the standard resistance, the bond as the unknown resistance, and the current normally flowing in the rail as the source of current. In the instrument casing are the ratio arms and the galvanometer for showing balance. A convenient feature of this form of bond tester is that the observer may select any rail length that he pleases, as that which a bond must not exceed if it is to be passed as "good," and, by simply setting the large needle to that length on the scale, observe the instant that the contact bar is put on the rail whether the bond is of higher or lower resistance, and hence to be condemned or to be passed.

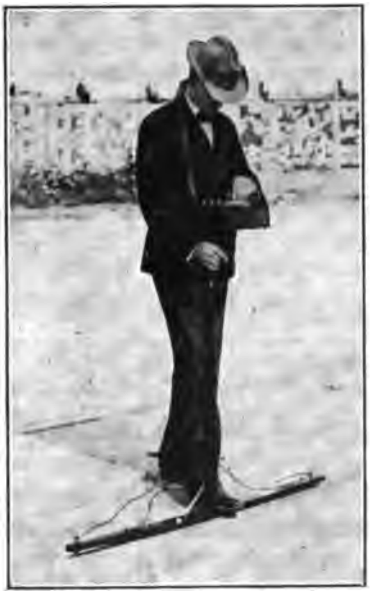

FIG. 100.

The galvanometer in these instruments, while sufficiently sensitive to enable the bond resistance to be read within a few inches of rail length even if but a single car is in operation, is robust enough to stand the potential due to a drop of over two volts across the bond without injury.

HIGH RESISTANCES.

Direct Deflection Method.

One of the most common methods of measuring a high resistance is to use a sensitive reflecting galvanometer and a source of high E.M.F., the latter being usually furnished by a set of 100 or more small batteries, mounted in a carrying case. The galvanometer should be provided with a shunt, to vary its sensibility; and a standard high resistance, usually of 100,000 ohms value, should also be available. The method of procedure is, first, to ascertain the sensibility of the galvanometer by placing the 100,000 ohms resistance in series with it, shunting the galvanometer with the highest ratio shunt, and then applying the battery. If, with a shunt decreasing the sensibility of the galvanometer to one ten-thousandth of the full sensibility and 100 cells of battery, the standard 100,000 ohms resistance placed in series with the galvanometer results in a galvanometer deflection of forty scale divisions, the deflection through one megohm with the same shunt ratio and the same battery would evidently be four scale divisions, and with the same battery, but a unity ratio shunt, 40,000 scale divisions, if such were within the capacity of the apparatus. If, now, the galvanometer be of a type in·which·the deflections are in direct proportion to the current flowing through the instrument, we have an equipment in which the existing battery would give 40,000 scale divisions deflection through one megohm in series with the galvanometer, and conversely one scale division deflection with 40,000 megohms in series with the galvanometer. If, therefore, the unknown resistance be inserted in the battery circuit, its value may be calculated directly from the deflection which the galvanometer shows.

If the order of the resistance to be measured be entirely unknown, it is advisable to use a high ratio shunt in connection with the galvanometer when making the initial readings, and subsequently to decrease the ratio until a point is reached where good readable deflections are had. It is better to use a shunt for the galvanometer than to attempt to accomplish the same end by decreasing the E.M.F. applied, because the insulators used to support the terminals of the unknown resistance permit of a minute but still appreciable flow of current, and the resistances offered by them to that flow are higher when the material is under the small stress caused by a low E.M.F. than when under the more usual working condition of a high E.M.F. It is particularly unsafe to assume that because, say, ten cells give a certain deflection through a given resistance, twenty will give twice that deflection, as the small batteries used in high resistance testing work are notoriously unreliable, and it is not often that any two of them will give the same potential after they have been out of the maker's hands for any length of time.

GUARD WIRES.

In a great many cases the resistance to be measured is that offered by the protective coating of a wire, and it is then usual to immerse the coil of wire in a metal-lined tank which can be filled with water, the coil terminals being left projecting above the surface. The resistance of the insulating coating on the wire is so high compared with that of the path through the large volume of water present, that the latter is negligible, and the resistance measured between the wire and the tank lining may be taken as the resistance of the insulation.

The insulation resistance is often of so high a value that the leakage path offered to the current over the surface of the insulating material from the point where the wire emerges from the surface of the water in the tank, shunts an appreciable fraction of the current and would, hence, introduce errors unless allowed for or prevented. To allow for it is extremely difficult, as its value varies constantly with atmospheric and other conditions. It may be largely prevented by cleaning and drying the exposed ends with alcohol, but is eliminated much more satisfactorily by using a "guard wire," as illustrated in Fig. 101. The guard wire is simply a few turns of fine copper wire wound over the surface of the insulating material near the point where this is cut away to allow the

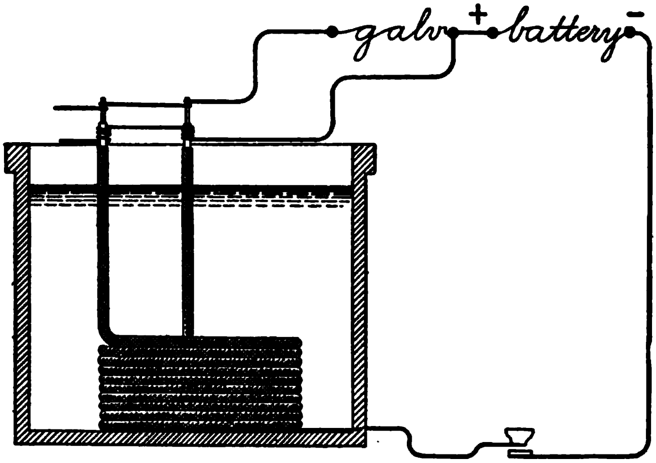

FIG. 101.

attachment of the main test wires. The wire connection is led past the galvanometer and direct to the batteries, so that any leakage current flowing over the surface of the wire insulation will be carried around the galvanometer and back to the battery again without affecting the galvanometer indications.

GALVANOMETER AND VOLTMETER METHOD.

When the source of E.M.F. that is available for making the resistance measurements is of uncertain and fluctuating value, a galvanometer can still be used to determine the value of the resistance, but the services of a commercial voltmeter must then be called into requisition also.

Fig. 102 shows the connections. The voltmeter is attached so that it indicates the potential between the terminals applied to the unknown resistance, and the galvanometer is connected in series with the latter in the usual way. The calibration of the galvanometer, namely, the number of amperes that must flow through it in order to produce one scale division deflection, must be known, as must likewise the resistance of the galvanometer.

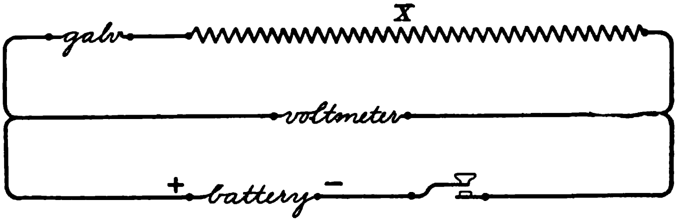

FIG. 102.

The galvanometer is used as an ammeter to measure the strength of the current which flows through the insulation, and the value of the resistance is calculated from Ohm's law; it being remembered, however, that the voltage indicated by the voltmeter is that existing between the terminals of the unknown resistance and the galvanometer connected in series with one another, and not that of the unknown resistance alone, so the result of the simple application of Ohm's law gives a resistance value equal to the sum of the unknown resistance and that of the galvanometer. To obtain final results, therefore, it is necessary to subtract the galvanometer resistance from the value derived as above. It is not feasible to change the voltmeter connections so that the voltage across the unknown resistance alone is indicated, as the galvanometer would then show the current flowing through the circuit composed of the unknown resistance and that of the voltmeter connected in parallel, and the latter is so low in comparison to the former, that an error of a small fraction of a per cent in measuring the total current flowing would make an error of many per cent, when the current flowing through X is computed by subtracting the known voltmeter current from the indicated total value.

LEAKAGE METHOD.

The resistance of the covering of an insulated wire may be measured by comparing the charge that it will give off immediately after being disconnected from a source of charging E.M.F., and the charge that remains after it has been disconnected from that source for a known period, the theory being that the difference has leaked through the covering at a rate that, of course, varies with the elapsed time. The preferred procedure in making a test according to this method is to immerse the coil of wire in a tank of water, one end being first carefully sealed, thus forming a condenser in which the inner coating is the conductor, the outer coating is the water, and the insulating covering the dielectric.

This condenser is first charged by applying a source of constant E.M.F., and is then allowed to stand for a measured number of seconds, say thirty. It is then discharged through a ballistic galvanometer and the throw, D_1, noted. The operation is then repeated with the same charging circuit, the period during which leakage through the insulation is allowed to take place after disconnecting the charging source being, however, made, say sixty seconds. Let the second deflection be D_2. If the two observed deflections were not too great, the resistance in megohms of the insulating coating is

$$R = \frac{t}{C \times \log_{10} \frac{D_1}{D_2} \times 2.303}.$$

The foregoing method must be used with discretion, because if the wire insulation is of a material with high electric absorbtive or "soakage" qualities, the results will be misleading.

DROP OF POTENTIAL METHOD.

If the standard resistance *S* and the unknown one *X* be connected together in series and current passed through them from a battery, *B*, as in Fig. 103, a reflecting electrometer, or electrostatic voltmeter, may be used to determine *X* in terms of *S* by connecting it first to the terminals of *S*, and then to those of *X*; whereupon the result is at once obtained in a manner analogous to that mentioned on page 117. No correction need be made in this instance for the resistance of the device that indicates the potential, as this is infinitely high as compared with the resistance of the objects under measurement.

A Thompson or D'Arsonval ballistic galvanometer can be used in place of the electrostatic instrument by charging a condenser first from the drop across *S*, discharging it through the galvanometer and noting the throw, and then by repeating the operation with *X*, in which case the throws are in the ratio of the resistances.

EVERSHED OHMMETER.

This is an instrument for measuring moderately high resistances, which shows directly from the position of a needle swinging over a calibrated scale the value in ohms of the resistance under measurement. It consists of two coils arranged with their axes at right angles to each other, one of which coils is connected in series with the source of current and the resistance to be measured, and the other, like a voltmeter, across the line from which current is supplied. At the point of intersection of the coil axes there is suspended, so as to be freely movable, a

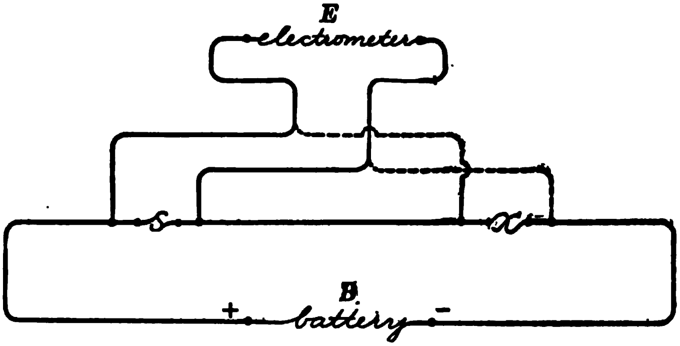

FIG. 103.

short magnetized steel needle. If the resistance be infinitely high, no current will flow through the series coil of the instrument; the needle will be influenced by the potential coil only and assume a position at right angles to its axis. If, on the other hand, the resistance be zero, and the current obtained from a source whose internal resistance is fairly high, current will flow through the series coil only, there will be practically no difference of potential between the points of attachment of the potential coil, and therefore the needle will assume a position parallel to the axis of the series coil. With finite resistances the needle is evidently influenced by the joint action of the fields of the two coils, tending to swing toward the infinity mark when the current is low and the potential high and *vice versa.*

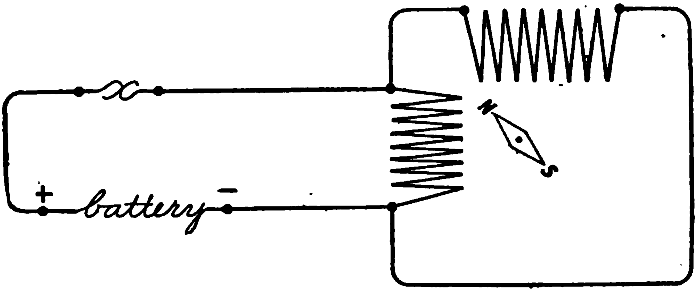

FIG. 104.

In the actual apparatus the source of current is a small hand-driven dynamo having permanent magnet fields, namely, a magneto which when driven at a reasonably constant speed supplies rectified alternating current at potentials of from 100 volts, in the case of instruments designed to measure resistances up to about 5 megohms to 500 volts for meters measuring up to 500 megohms. Theoretically, the calibration of this ohmmeter can be calculated from the geometrical dimensions of the apparatus, the number of turns of wire, etc., but practically it is better to graduate the scales empirically by comparison with resistances of known value. A diagram of the connections of the instrument is shown in Fig. 104.

In the early form of this ohmmeter, the moving needle was of steel magnetized as above mentioned, but this was open to the objection that the needle was readily influenced by comparatively feeble stray magnetic fields, even those of the hand generator which supplied the current. In the more modern form of apparatus a soft iron needle is employed, which, while resulting in a shorter scale because the zero must be placed in the center instead of at one end, enables the user to eliminate the effect of stray fields, by reversing the current and taking the mean of the observed indications. The current reversal is readily effected by turning the crank in an opposite direction, thus reversing the direction of the rotation of the magneto armature.

SPECIAL CONDITIONS.

The foregoing outline of methods of measuring resistances of different values treats only of the measurement of simple circuits, such as the resistance of a metallic body, or a poor conductor in which no disturbing factors, such as local E.M.F.'s exist. In practice, however, disturbing E.M.F.'s are frequently present, being either existent before the measurement is attempted, as in the case of a battery, or being set up by the passage of the current employed in measuring the resistance, as in the case of an electrolyte. These E.M.F.'s tend to cause currents to flow in the network of conductors, which are ordinarily necessary in measuring resistances, and make the indications of the galvanometer or telephone receiver, used as the current detector, erroneous. In the following we will take up the methods of measuring the resistances of circuits which contain these disturbing elements and are frequently met with in practice.

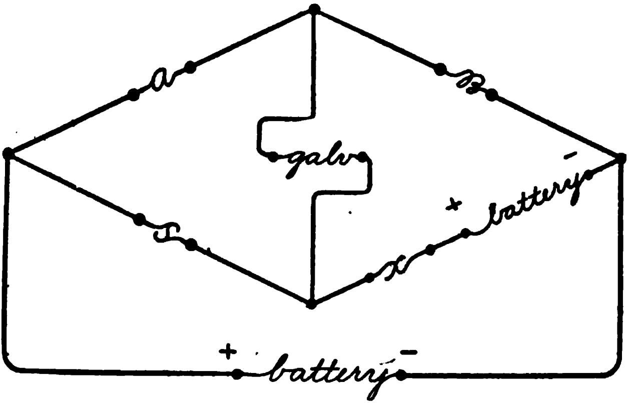

FIG. 105.

RESISTANCE OF ELECTROLYTES.

Any liquid not a melted metal, such as mercury, fused lead, etc., which is a conductor of electricity, is an electrolyte, and all electrolytes are decomposed when current flows, the decomposition setting up an E.M.F. opposing that of the source that forces the current through it. This fact makes it impossible to measure the resistance of an electrolyte with the ordinary Wheatstone bridge arrangement. Referring to Fig. 105, if the X arm of the elementary Wheatstone bridge shown in the figure contains in itself a source of E.M.F. the correct value of S, which must be inserted to make the ratio $\frac{A}{B} = \frac{S}{X}$ hold good, is no longer attained when the galvanometer shows no deflection, as, where an ordinary resistance would keep the difference of potential between the junctions of AB and SX alike, a source, X, that contains in itself a source of potential difference will cause a flow of current through the bridge network under the same circumstances and show a galvanometer deflection.

Kohlrausch Bridge.

In measuring the resistance of an electrolyte, one way of overcoming this point is to use, instead of the direct current which calls forth the counter E.M.F. of the electrolyte, an alternating current with the current reversals succeeding each other so rapidly that decomposition at either pole is immediately recomposed and the disturbing E.M.F. set up in one direction, offset by an immediately following and opposite one.

Kohlrausch first suggested the above method and used for the measurement of the resistance of electrolytes an ordinary slide-wire bridge of the type shown in Fig. 72, obtaining the current applied to the slide wire terminals from the secondary winding of an induction coil actuated by a battery. If the induction coil core be of hard iron, or even steel, the secondary current becomes very nearly a pure alternating current with smooth, symmetrical waves, a feature that is necessary to secure good results.

The ordinary Thompson or D'Arsonval types of galvanometers cannot be used as current detectors with this form of bridge because they respond only to direct current.

Their place is usually taken by a telephone receiver and when the sliding contact is moved along until a point is reached where the receiver no longer gives forth a humming sound, the value of the resistance of the electrolyte can be calculated or read off exactly as in the case of the same instruments used with direct current for the measurement of ordinary resistances.

The frequency of the alternating current used must be high, because if the current reversals follow one another too slowly, polarization may take place.

With the frequency obtainable with the interrupter of an ordinary induction coil, fairly good results are obtainable, but it is claimed by Duddell that the frequency must attain, at least, 10,000 alternations per second if polarization errors are to be entirely eliminated.

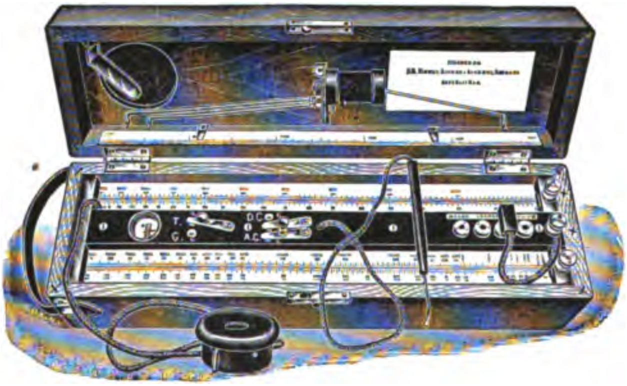

FIG. 106.

No orthodox Kohlrausch bridges are made in this country, but the Hanchett-Sage ohmmeter described on page 107 is often used for such work. A special model of this instrument with the induction coil for supplying the alternating current permanently fastened in the cover, and with the wiring connections self-contained, is shown in Fig. 106. The galvanometer shown as built into the instrument, responds to direct current only, and is used for other tests, it being possible to throw either it or the telephone receiver into circuit to act as the current detector by means of a switch provided for that purpose.

Secohmmeter Method.

A galvanometer which responds to direct current only can be used when the direction of the current flowing through the electrolyte is being continuously reversed, if the connections to the galvanometer be simultaneously reversed. The apparatus for bringing about these two reversals simultaneously is the secohmmeter illustrated in Fig. 107. The device consists of a commutator, rotated by hand by means of a crank, and having bearing thereon, contact brushes through whose aid the direction of the current flowing through both circuits is continuously reversed. It is necessary to rotate the handle at a high speed, as the current reversals must, as before explained, succeed each other with sufficient rapidity to annul the polarization effect. The galvanometer movement must be heavy, so as to possess inertia sufficient to prevent its swinging back and forth in an attempt to keep step with the pulsations of the current. With these conditions fulfilled, the resistance of an electrolyte may be measured by the Wheatstone bridge method, and a secohmmeter with the same ease as that of any metallic circuit.

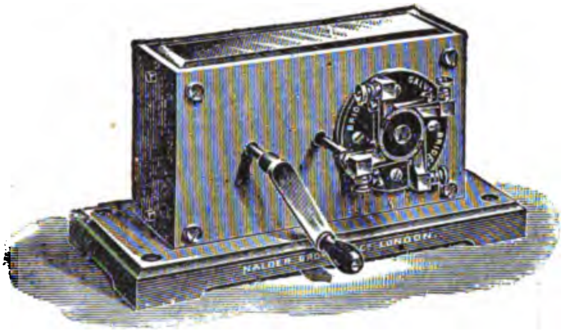

FIG. 107.

Stroud and Henderson Method.

This is entirely different from any of the foregoing, and consists of an ingenious modification of the ordinary Wheatstone bridge. Referring to Fig. 108, T_1 and T_2 are two tubular vessels containing the electrolyte, similar as to diameter and nature of terminals, but differing in length by a known amount. P and Q, the two other arms of the bridge, are made of very high resistance, say 20,000 ohms each, this being desirable, as the resistance of electrolytes is high, and it is always desirable in Wheatstone bridge measurements to have the resistance of the four arms of the same order. The galvanometer should also be of the high resistance pattern. To obtain results, R, which is an adjustable resistance, is manipulated until the galvanometer shows no current, whereupon the ratio $\frac{T_1}{T_2 + R} = \frac{P}{Q}$ obtains. As the electrolyte in T_1 and T_2 is the same, the polarization E.M.F. of the branch containing T_1 is exactly neutralized by the polarization E.M.F. in the branch T_2, and the actual resistance per unit length of column of electrolyte may be calculated from the ratio just given.

In measuring the resistance of an electrolyte by any of the foregoing methods the liquid is usually placed in a U-shaped glass vessel, as shown in Fig. 109. The cubic contents per unit of length of tube are carefully determined and the tube length itself is measured with care. The tube ends are made as large cups in order to allow of the introduction of electrodes of considerable size. With almost all electrolytes the electrodes must be of platinum, sometimes, in order to obtain the large area that is necessary to give an efficient contact between the electrode and the liquid, of corrugated platinum sheet. It is more usual, however, to use an electrode of spongy platinum, or, still better, sheet platinum coated with a deposit of platinum black. In all drop of potential methods of measurement it is desirable to use a separate pair of electrodes to make contact with the column of liquid at a known distance apart in order to eliminate an error due to the contact resistance between the main terminals and the electrolyte.

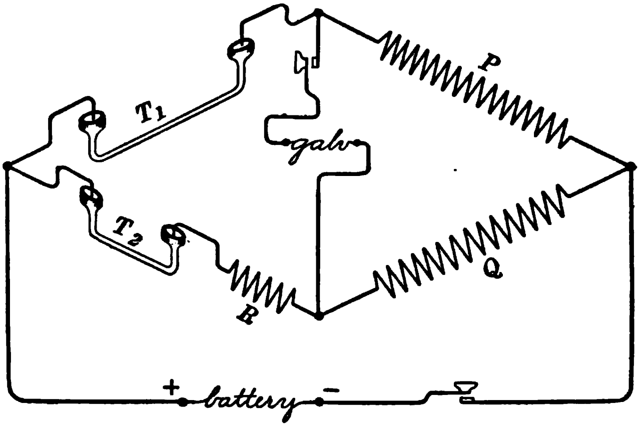

FIG. 108.

Instead of determining the volume of the contents of an electrolyte tube, and from this, by measuring the length of a section, the average cross-section of a column of the liquid, it is usually much more convenient to obtain the resistance in terms of that of a liquid whose resistance per unit volume is known. Mercury is often used as the standard in this way, the tube being first filled to a certain level with this and the resistance measured, the performance being then repeated with the same volume of the liquid under test. The ratio of the results is then the ratio of the specific resistance of mercury to that of the solution being investigated. A standard solution that is itself an electrolyte is even better than mercury. Favorite liquids of this class are sodium chloride ($NaCl$), a solution of which having a specific gravity of 1.201 has a resistance of 4.66 ohms per cubic cm. at 18° C. and a temperature coefficient of .0234, and copper sulphate ($CuSO_4$), a solution of which having a specific gravity of 1.208 has a resistance of 29.37 ohms per cubic cm. at 18° C. and a temperature coefficient of .0241 (both according to G. Wiedermann).

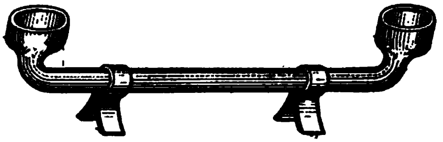

FIG. 109.

One point to be borne in mind in connection with methods using alternating current and a Wheatstone bridge network of conductors is that the resistance coils and wires forming the four arms of the bridge must be arranged so as to have no inductance and no capacity, because, except in the almost impossible event that the inductances and capacities are all alike, the different time constants of the different branches will throw the currents in them out of step, and it will be impossible to obtain any balance at all. This is one reason why the slide-wire type of bridge is usually employed, a straight stretched wire having negligible capacity and inductance.

Ayrton and Perry Method.

In the Ayrton and Perry method of measuring the resistance of an electrolyte, the liquid is poured into a containing vessel, shown in Fig. 110, and current passed through it with the aid of the platinum wires projecting from the sealed ends of glass tubes immersed in the liquid. A resistance in the circuit enables the strength of the current to be regulated, and platinum wires sealed into the ends of two other glass tubes, *W* and *W*, are used to make connection with a reflecting electrometer.

As the electrometer is of infinite resistance, it draws no current through the contacts, *W* and *W*, hence there is no polarization, and the electrometer shows the true difference of potential between these points. From this and the known strength of the current flowing through the electrolyte, as indicated by the milliammeter in the supply circuit, the resistance may at once be calculated.

Hering's Liquid Potentiometer.

A modification of and improvement on the foregoing method has been described by Hering. (See Transact. of the A. I. E. E., Feb., 1902.) In this a trough of known cross-sectional area is used to contain the electrolyte, and current is passed through the solution by means of plates, *a* and *b*, immersed therein, as shown in Fig. 111.

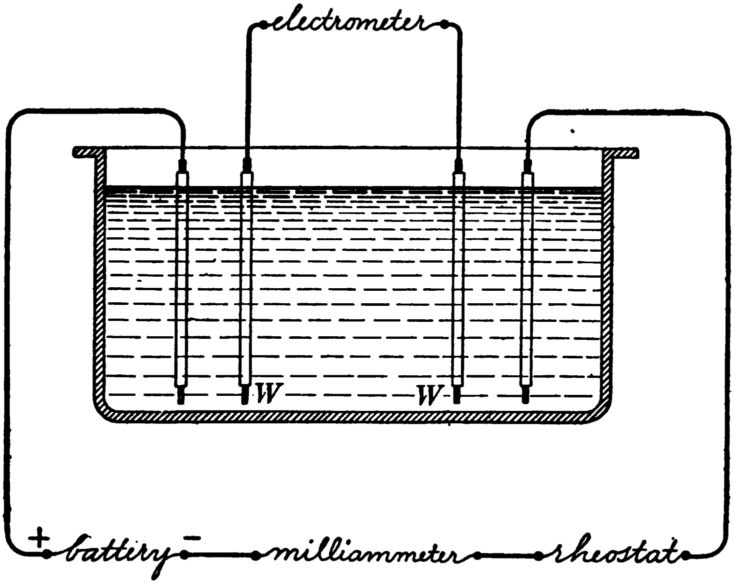

FIG. 110.

The strength of the current flowing is measured by a suitable ammeter. There is provided also a galvanometer, *G*, for detecting the presence or absence of current, and a cell or group of cells, *E*, of known potential. A voltmeter, *V*, is desirable in order that the potential of *E* may be seen at a glance, but if *E* is a standard cell, it must, of course, be dispensed with. If the two plates, *f* and *e*, connected up to the galvanometer, cell and voltmeter as shown, be immersed in the solution so that the E.M.F. between the points of immersion is opposed to that of the cell *E*, the distance between *e* and *f* can be varied until the galvanometer, *G*, no longer shows a deflection.

The potential between *e* and *f* is evidently that of the cell, *E*, and as the distance between these points may be read off from the scale shown on the edge of the containing vat, the resistance of the solution can be calculated, since we know the cross-sectional area of the liquid column from the size of the vessel and the depth of the liquid, the current strength from the instrument *A* and the drop in potential due to the resistance from the E.M.F. of *E*. According to Mr. Hering, the electrodes, which should, of course, be of the same material, must not be attacked by the electrolyte, or by the products of decomposition of the electrolyte, before balance can be attained. The latter condition makes it impossible to use the platinum sponge or platinum black electrolytes which are employed when making the measurements by the above-mentioned Kohlrausch method, since both store up large quantities of gas. Carbon was found to possess the same property to an appreciable degree, and gold

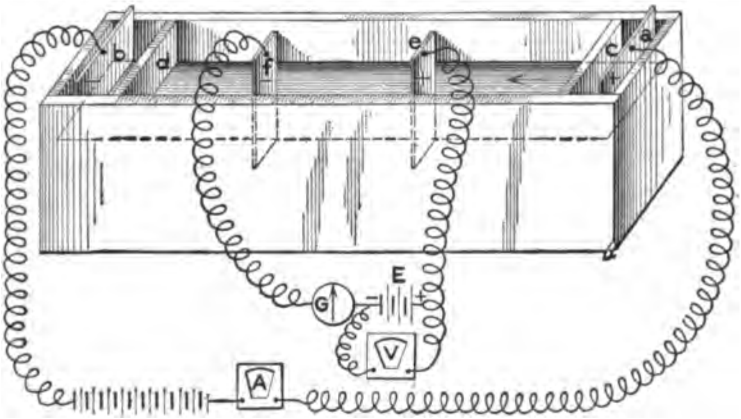

FIG. 111.

seems to have been the only satisfactory metal. The method is of interest, as it does not call for any special apparatus, it being possible to use an ordinary commercial pattern pivoted millivoltmeter, or shunt type ammeter without its shunt, as the galvanometer, G.

INTERNAL RESISTANCE OF BATTERIES.

In making certain measurements it is necessary that the internal resistance of the battery supplying the current be known. There is a large number of methods for ascertaining this quantity, but only a few of these, which are of easy application with commercial apparatus, will be considered.

Half-Deflection Method.

In a simple circuit, such as that shown in Fig. 112, comprising a battery, galvanometer, or milliammeter, and an external resistance, let the resistance of the various elements be called R, G, and r, respectively. If the E.M.F. of the battery be called e, the current, i, flowing through the whole circuit, is $i = \frac{e}{R + G + r}$. By increasing r, i may be reduced to one half the original value, in which case we have $\frac{i}{2} = \frac{e}{R + G + N}$, in which N is the new resistance of r. From these two equations we deduce the value of R, $R = N - 2r - G$. This method, which is a very simple one, is capable of giving results of considerable accuracy.

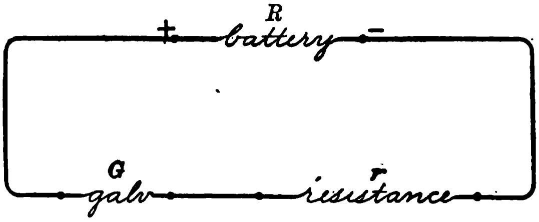

FIG. 112.

Mance's Method.

In this method the ordinary Wheatstone bridge is used, with only two changes of connections; namely, the battery is connected in the place ordinarily occupied by the unknown resistance, and in the place ordinarily occupied by the battery there is connected a key for closing the circuit. The galvanometer retains its ordinary position. The arrangement is shown in Fig. 113. When the key, *K*, is open, there is a current through the galvanometer, giving a definite deflection, which, as will be explained presently, can be made of convenient magnitude. If the key, *K*, be now closed, and the deflection of the galvanometer remain the same, the bridge is balanced and the resistance, x, of the battery, is $x = \frac{a}{b}c$. Should the closing of the key, *K*, alter the deflection of the galvanometer, the resistance of the rheostat, c, must be altered until the deflection is the same with *K* open or closed. There is a high resistance, *R*, in series with the galvanometer, which latter is provided with the usual shunt. By this means the current may be regulated so that a convenient deflection is obtained while still keeping the total resistance of the circuit high, thereby preventing the running down of the battery. With this same end in view, the the ratio arms, a and b, are of as high resistance as practicable. This method when properly handled gives satisfactory results, but the limit of accuracy is much less than that of ordinary Wheatstone bridge measurements of resistance, because in these measurements a zero method is used, which is limited in accuracy only by the limit of sensibility of the galvanometer, while the limit of accuracy of Mance's method is that of a

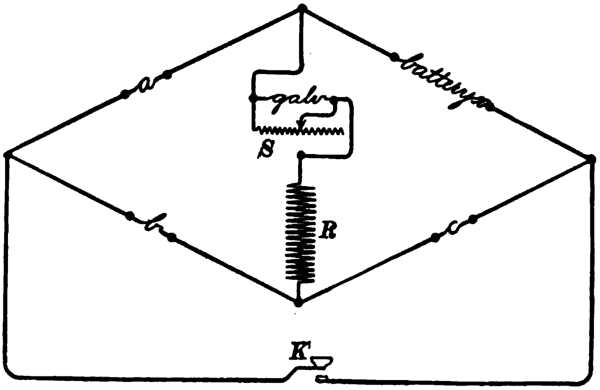

FIG. 113.

scale reading, usually not greater than one part in three or four hundred. This, however, is usually sufficient in practice, for the resistance of a cell is a very uncertain quantity and liable to change on very slight provocation. Mance's method is fully as accurate as the half-deflection method.

Method Using Alternating Current.

If a source of alternating current be used in place of the usual direct current, the internal resistance of a battery may be measured by the regular Wheatstone bridge method, provided that the bridge arms are without inductance or capacity, and that the current detector is one that responds to alternating current *only*, and does not indicate the presence of the direct current which the battery under test will cause to circulate in the bridge network. A telephone receiver fulfills this requirement if the galvanometer key or device corresponding thereto be kept closed during the test, as the continuous current will merely put a steady stress on the diaphragm, still leaving it free to vibrate when alternating current flows. The special Hanchett-Sage ohmmeter, illustrated on page 140, may be used for this test, in which case the stylus must be slid instead of tapped along the slide wire.

It should be noted that this test gives the internal resistance of the battery when the same is delivering current, that is to say, its open circuit resistance plus that due to any polarization that may have taken place.

Where the galvanometer employed responds to *both* direct and alternating current, as, for instance, a reflecting electrodynamometer, it is necessary to test two identical cells at a time, connecting them in opposition in the X arm of the bridge, as shown in Fig. 114, in order that their potentials may balance one another and no current be caused to flow through the network. It is evident that the value of the resistance obtained is double that of a single cell.

It will be noted that this second method gives the true internal resistance of the cells under open circuit conditions.

The remarks under the measurement of the resistance of electrolytes as to the necessity of a high frequency of the alternations and that the current must be a truly symmetrical one, apply with the same force to these tests.

Internal Resistance of Storage Batteries.

Where the internal resistance of the battery to be measured is very low, as, for instance, in the case of a storage battery, it may be measured very simply in another way involving only the use of an ammeter and a low-reading voltmeter. With the latter the open circuit E.M.F. of the battery is first taken. A heavy current is then drawn from the battery and its strength measured by the ammeter, the E.M.F. at the battery terminals being simultaneously measured with the voltmeter as before. This gives us two equations connecting e, i, and r, and from them we have $\frac{e - e'}{i} = r$, where e = open circuit voltage, e' = closed circuit voltage, r = resistance, and i = current. Similar measurements may, of course, be made when the cell is charging instead of discharging.

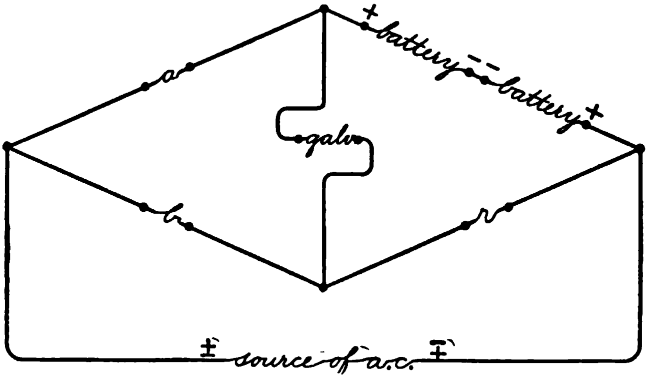

FIG. 114.

RESISTANCE OF GALVANOMETERS.

It is more often necessary to know the resistance of a galvanometer than that of the cells themselves. The ordinary methods of measuring medium resistances, before mentioned, can seldom be used for this purpose, as they all call for a battery current which is usually so high as compared with the capacity of the galvanometer that the latter would be burned out if any such proceeding were attempted. There are, however, other ways of obtaining this information about a galvanometer, the more usual ones being as follows:

Half-Deflection Method.

This is worked in the same way as the half-deflection method for determining the internal resistance of a battery; that is to say, by letting a certain current flow through the galvanometer and then inserting sufficient additional resistance to bring the galvanometer deflection down to one half. From the same formulæ given in the above paragraph we evidently have $G = N - R - 2r$, which may be written $G = N - 2r$, if the internal resistances of the battery, R, be negligible, as compared with the resistance of r and of the galvanometer.

Thompson's Method.

If the galvanometer be inserted in one arm of the Wheatstone bridge, as diagrammatically illustrated in Fig. 115, and for the galvanometer, usually inserted between E and B, there be substituted a contact key, the value of the resistance, b, may be varied until the galvanometer shows the same deflection whether the key is raised or depressed. When this state of affairs is reached, the resistance of the galvanometer equals $\frac{ad}{b}$.

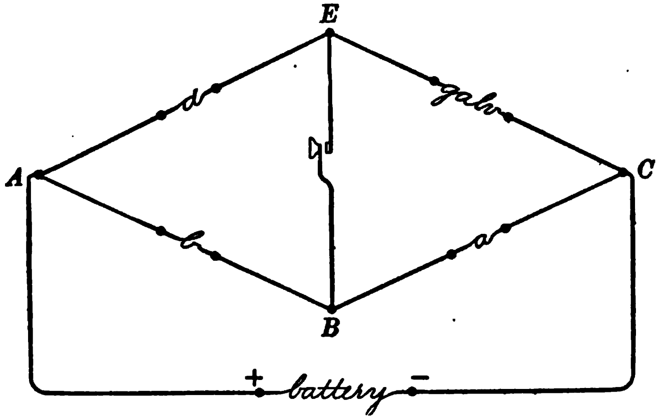

FIG. 115.

The same test can be made by substituting for the type of Wheatstone bridge in which plug resistances are used the slide wire form, in which event the key between E and B is dispensed with, ABC becomes the bridge wire, and the point of contact, B, is adjustable and forms the sliding contact. In this case, also, the galvanometer resistance equals $\frac{ad}{b}$, and since the ratio of a to b alone enters into this equation the absolute values of a and b need not be known.

CHAPTER VI.

MEASUREMENT OF CURRENT.

INSTRUMENTS for measuring electric currents may conveniently be divided into three classes; namely, those suited for measuring direct currents only, those for alternating current only, and those that can be used for both direct and alternating current.

Beginning with the direct current instruments, and leaving aside purely laboratory apparatus, such as the voltmeter, the first commercial apparatus to be considered would logically be the potentiometer. This device has already been minutely described in the chapter on laboratory standards for current measurement, and is referred to here because under favorable conditions it can be used in the commercial measurement of current strength.

By far the greater proportion of instruments for the measurement of direct current fall under another heading, and are of types in which the current strength may be read off directly from the position of an indicating device relative to a marked scale. Many of such instruments contain permanent magnets, upon whose constancy depends the constancy of the accuracy of the indications. The class may be divided into two general types: one in which the winding through which the current to be measured is passed is held stationary, while a permanent magnet, or a soft iron magnet polarized by a stationary magnetic field, is deflected; the other in which the magnet is stationary and the wire through which the current passes is movable.

FIXED COIL INSTRUMENTS.

The commercial apparatus in most extensive use falling under the first class indicated is of the type developed by Deprez and Carpentier and by Ayrton and Perry many years ago. In this a magnet, *NS*, Fig. 116, saturates magnetically a soft iron needle, *sn*, and tends to hold the latter constantly in the position shown, as then there is offered a minimum resistance to the flow of the lines of force from one pole of the magnet to the other. The coil of wire, *CC*, through which the actuating current flows is wound on a spool, so that it forms a solenoid whose axis is at right angles to that of the needle. Current flowing through this solenoid affects *sn*, just as the coil of a Thompson galvanometer (see page 56) causes the magnetized needle suspended within it to deflect and tend to take up a position where its axis is parallel to the axis of the coil. An increased current strength of course exerts an increased force tending to deflect *sn*, and the needle will therefore come to rest only when this increased effort is balanced by the effort of the magnet, *NS*, to pull *sn* back to its original position, which effort evidently increases as the extremities of

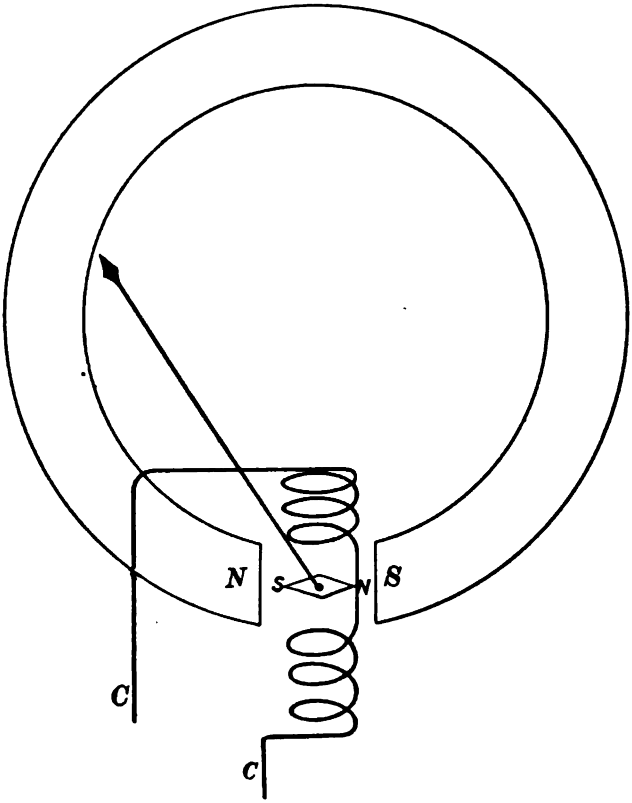

FIG. 116.

sn recede from the poles *NS.* By suitably dimensioning the parts and shaping the polar faces of *SN*, the opposing force, due to the attraction of the fixed magnet, may be made to increase for increasing deflection at the same rate as the effort tending to turn the needle, due to the current flowing through the coil, and therefore the scale, over which the index actuated by the moving needle sweeps will be graduated in divisions of equal width for equal current increments.

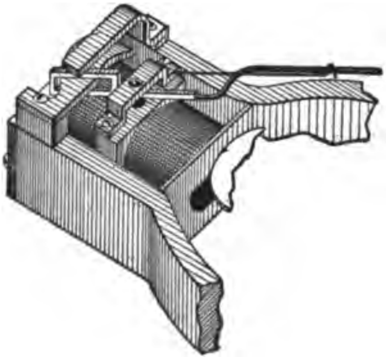

FIG. 117.

The original form of this type of mechanism had the disadvantage that when the current strength changed abruptly the index did not show the new value at once, but vibrated back and forth on its scale for a considerable period. This can be overcome to some extent by making the moving parts extremely light, in order to diminish their inertia, and by making the magnetic field very powerful, which of course results in a greater effort to prevent the needle from swinging past the point where equilibrium exists between the directive force of the magnet and that of the solenoid, that is to say past the line whose direction is the resultant of the fields due to the permanent magnet and the current-carrying coil. A greater magnet strength means, however, a decreased sensibility and increased cost of structure, so that a limit in this direction is soon reached. The damping of the oscillations that would still exist may be accomplished, either by an air vane moving in a nearly closed box and forming an air dash pot or by an oil dash pot. It may also be attained magnetically by attaching polar extensions to the magnet, as shown in Fig. 117, which extensions supply a field through which is swept a short-circuited conductor moving with the movable element. Currents are set up in this short-circuited loop when the needle swings, just as in the case of a short-circuited armature coil, and are dissipated by doing the work necessary to overcome the loop's resistance.

The energy so dissipated is subtracted from that which tends to carry the moving system past the position of equilibrium, and therefore results in reducing very materially the number of swings and the time to obtain a reading.

Another commercial-indicating instrument suitable for direct current measurements only and containing a stationary permanent magnet and a fixed coil of wire, is one made by the Whitney Electrical Instrument Company.

Referring to Fig. 118, *NS* is a U-shaped permanent magnet, and *sn* a short piece of soft iron secured diagonally to the shaft, *B*, and rotating with it. *A* is a stationary spool containing the windings, *C*, through which the current to be measured is passed, *I* is a pointer for indicating the extent of rotation of the shaft, and *D* is a spring opposing that rotation. The iron piece, *sn*, is evidently polarized by the stationary magnet, just as is the needle *sn* in the Deprez-Carpentier instrument, Fig. 116, but the stationary magnet does not exert any effective directive force in this case, as whatever the position that *sn* may take up by the rotation of the shaft, *B*, the distance between its extremities and the inner faces of the magnet, *NS*, remains the

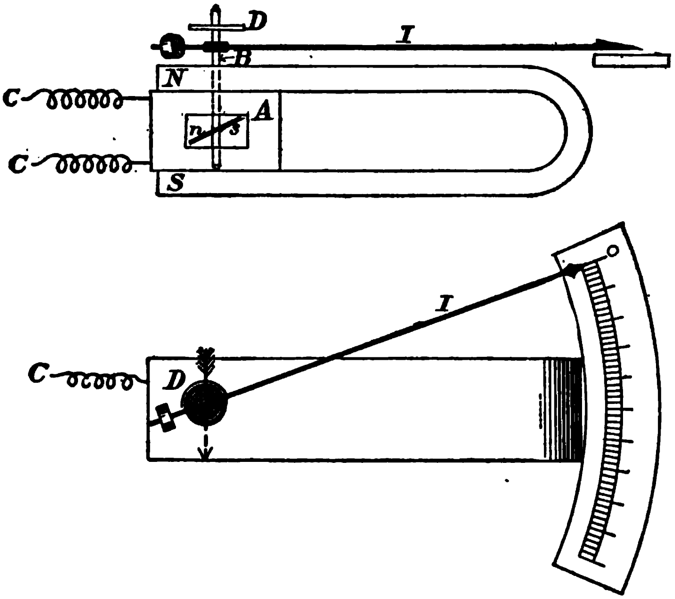

Fig. 118.

same, and hence there is no increased or decreased effort to pull it back. When current flows through the coil, *C*, it sets up a magnetic flux in the direction of the dotted arrow shown in the plan view of the mechanism, and the polarized needle of course tends to take up a position parallel thereto. The force with which the needle tends to rotate is in proportion to the current strength, and as the spring, *D*, supplies an opposing force in proportion to the amount that it is wound up by the rotation of the shaft, each current strength has a corresponding position of equilibrium of the needle, *I*, and therefore the scale under *I* may be calibrated directly in units of current strength.

These instruments are damped by means of aluminum vanes secured to the shafts and swinging between the jaws of a small auxiliary magnet. Eddy currents are set up in such a vane when it moves, and these check the swings as before explained. The form is considerably more sensitive than the older Deprez-Carpentier ones.

MOVING COIL INSTRUMENTS.

If the d'Arsonval galvanometer mentioned on page 46 be graduated by comparison with some standardized current-measuring instrument, it may be and often is used as a milliammeter, or millivoltmeter. Such apparatus is, however, clumsy and unnecessarily sensitive, and the use of a beam of light for taking the readings is rather inconvenient. In instruments of this class for the 'regular measurement of commercial current strengths the suspension strips of the reflecting galvanometers are replaced by pivots working in jeweled bearings, and a needle attached to the coil is moved by it over a calibrated scale, instead of the mirror and light beam arrangement, a commercial moving coil instrument, thus forming the same modification of the d'Arsonval galvanometer that the Deprez-Carpentier instrument forms of the Thompson galvanometer.

A common form of this d'Arsonval type of ammeter, built along the above lines, is the well-known Weston instrument, whose mechanism is shown in Fig. 119. The rotation of the active coil in this and similar meters is opposed by a pair of flat spiral springs whose inner ends are electrically connected to the coil terminals, and whose outer ends are secured to fixed abutments through which the current is led into and out of the apparatus. The springs offer an opposing force that increases in direct proportion to the angle through which they have been wound up, and, as the torque increases in direct proportion to the current strength, equal current increments produce equal increments of the excursions of the needle, that is to say, the scale is equally divided.

In this instrument, as in the original d'Arsonval form, the tendency of the coil to oscillate about the point of equilibrium before coming to rest is obviated by winding the moving wire on a frame of metal of good electrical conductivity, such as copper or aluminum. This frame acts like a short-circuited conductor in a motor armature, and, as stated before, consumes energy which is subtracted from that due to the inertia which tends to swing the needle beyond the position of equilibrium.

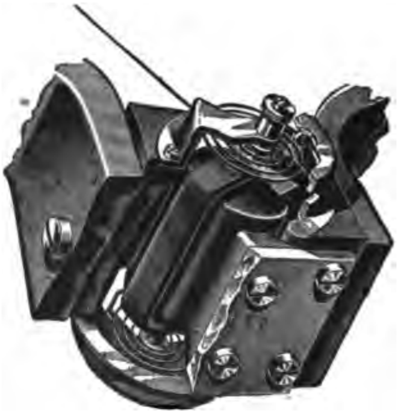

FIG. 112.

The strength of the currents that can be passed through the winding of an instrument of this description is very small as compared with those used in most commercial work, as the springs, which serve also as conductors, become overheated and lose their proper elasticity if a very small current flow through them be exceeded. In order to render the apparatus available for the measurement of large currents, the same expedient is used as that employed in the case of reflecting galvanometers for decreasing their sensibility, and incidentally increasing the amount of current that may flow through the galvanometer circuit without injury, that is, by using a shunt and diverting the major portion of the current through that by-path. The remarks made on the subject of shunts for use with the potentiometer when measuring current strengths (see page 89) also apply to shunts for such ammeters.

An ammeter made by the Whitney Electrical Instrument Company differs from the conventional d'Arsonval form, in that, among other things, there is only one gap in the magnetic circuit, instead of the usual two, and that the coil of moving wire is not symmetrical to the axis about which it rotates.

Fig. 120 illustrates the mechanism of this type of instrument, the outer pole piece of the magnet being shown as transparent in order that the coil arrangement may be seen more clearly. As in the case of the Weston meter, the indications of the Whitney device are made "dead beat" by winding the active wire on a spool of copper or aluminum, the currents generated in the spool tending to bring it rapidly to rest. However, the action is not as efficient as in the other form, because in order to balance the moving element mechanically, so that a small difference in the angle to the horizontal at which the meter is used will not introduce an appreciable error, a counterweight is added on the side of the supporting shaft opposite the coil, and the inertia of this carries the needle slightly beyond the position corresponding to the new current strength, when that current is applied, and time must elapse before it can swing back again and indicate the true value. On the other hand, the construction is advantageous in affording very perfect shielding against disturbances due to neighboring magnetic fields, and also in that it allows the use of a greater clearance between the coil and pole pieces.

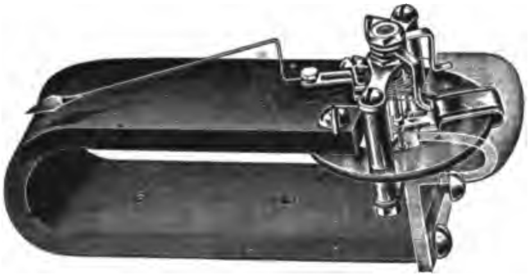

FIG. 120.

The Kennelly ammeter is shown in Fig. 121. In this as in the Whitney instrument it will be seen that there is but a single air gap in the magnetic circuit; the moving conductors, however, instead of being wound into the form of a loop are distributed radially on a flat disk, and the disk itself is made of a good conductor, such as aluminum, which damps the swing of the indicating needle, not as in the case of the two preceding instruments, by setting up currents as in a short-circuited turn of motor or generator armature, but by the eddy currents generated. There is a considerable amount of inactive wire in the moving element of this class of instrument, because, in order to avoid leading the current back through the same magnetic field, which would render it inoperative, the turns must be carried around the periphery of the disk for a considerable portion of its circumference before they can again be led back to the center and the two ends connected to the flat spiral springs, to which electrical connection is made with the outside line, and which exert the force opposing the motion of the disk.

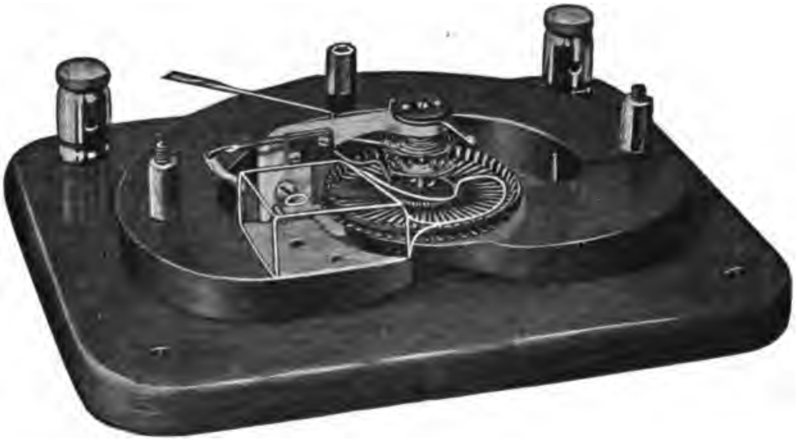

FIG. 121.

A somewhat similar instrument is the Thompson ammeter, shown in Fig. 122. In this as in the Kennelly meter the moving wire is mounted on a flat disk, but instead of having the individual conductors follow along separate radii, they are bunched and flow along a single diameter, being symmetrically divided into halves, the return halves of each portion being led along opposite semi-circumferences. The form of stationary magnet, which furnishes the magnetic field necessary for the operation of the instrument, is also different from that in the Kennelly instrument. There are two of these magnets placed with their poles of unlike signs adjacent. While the necessity of two magnets enhances the first cost, their use has the advantage that, if the instrument be placed in a powerful magnetic field, whatever additional field strength is caused by this between the poles of one of the magnets is offset, so far as the action on the movable coil is concerned, by the weakening of the magnetic field of the other magnet. In other words, the instrument is astatic. This point, however, is of more theoretical than practical importance, as the Whitney form is practically as immune from external influences, and any of the meters described may be so effectively shielded, for commercial purposes at least, by placing them within an iron casing that no further protection is needed.

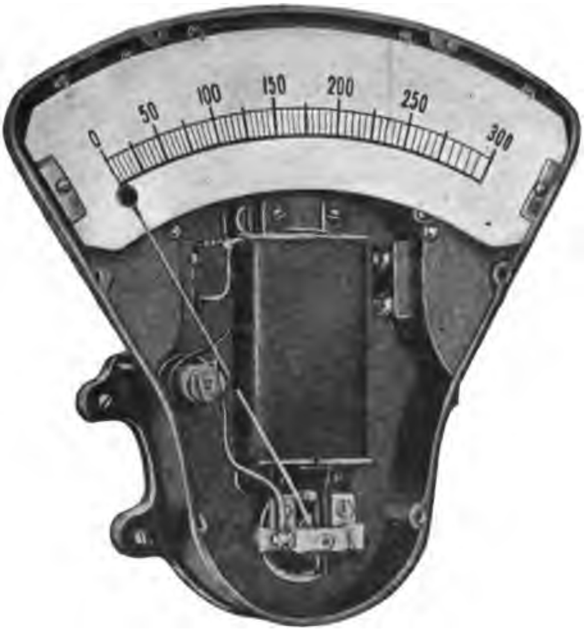

FIG. 122.

The three types of moving-coil instrument mechanisms that have been briefly mentioned above were selected in order to emphasize what has been mentioned in a preceding chapter, namely, that coil instruments for the commercial measurement of direct current are nothing more or less than special electric motors, in which the field magnet is stationary as usual and the armature allowed to rotate against the constantly increasing resistance of a spring until the point of balance is reached.

A, Fig. 123, makes it clear that the original d'Arsonval form of instrument, as exemplified by the Weston ammeter, is a small motor with a permanent magnet field, having a stationary armature core and a section of armature winding of the conventional series or drum wound type as moving element. *B* of the same figure shows that the Whitney form of ammeter is likewise a small motor with a permanent magnet field, a stationary armature core, and one section of armature coil of the Gramme pattern as the movable element; whereas the cuts *C* in the same figure show that the Kennelly and Thompson instruments are motors having armatures of the radially wound form. In each case the opposing force may be that furnished by a flat spiral spring or springs; gravitational attraction is sometimes employed when the apparatus is placed in a favorable position, or magnetic attraction on an iron needle (see page 52) may be used. It is usual to conduct the current to and from the moving coil through the springs, but separate flexible conductors may be used if the springs be absent, or if it is desired to electrically reinforce the capacity of existing springs.

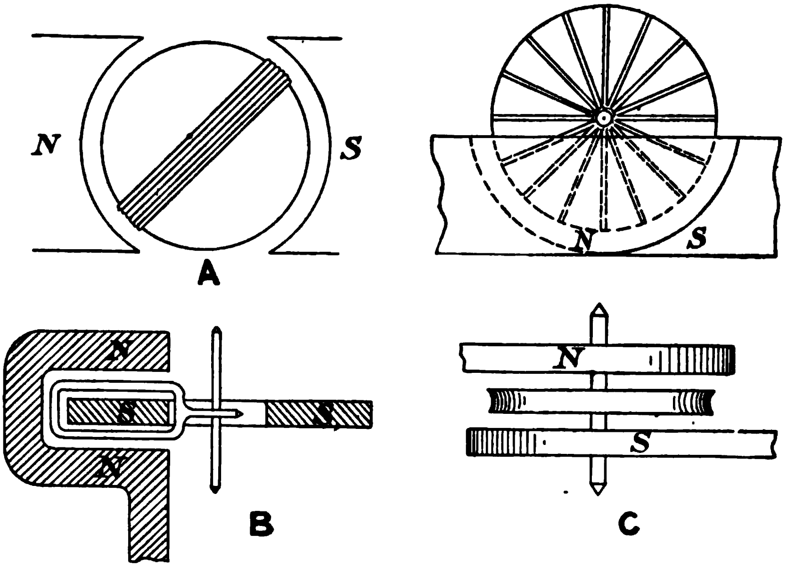

FIG. 123.

In all of the forms it is impossible to pass all of the current to be measured through the moving coil unless the current be of very small value, and recourse is had, therefore, to shunts for diverting the major portion of the current, as already mentioned in connection with galvanometers in Chapter III.

Shunted ammeters of the types so far described have two great advantages: first, their scales are equally divided, which means that when used to measure the output of constant potential generators or the load on such circuits, the percentage of full load being carried may be estimated at a glance from the angular position of the pointer, much as time is casually read off from a clock from the relative position of the hands without looking at the numerals on the dial. Second, and more important, the amount of current needed by the instrument itself to produce full scale deflection is so very small that it is easily carried by light flexible conductors, the shunt leads, with the result that the instrument may be placed in any convenient position, irrespective of the location of the bus-bars, the shunt only, carrying the predetermined remaining part of the current, being inserted in the main circuit.

On the other hand, it is rarely the case that a shunted ammeter will give as accurate results as an instrument in which the whole current to be measured is passed through the instrument windings. First of all, there are the temperature errors. In order that the windings of commercial shunted ammeters may have the requisite sensibility they are of necessity composed largely of copper wire, a material whose resistance changes about 1 per cent for every 5° Fahr. change in temperature. Therefore if the shunt is of a material having a practically zero temperature coefficient, the changes in resistance of the instrument windings become important. The temperatures at which instruments are used commonly cover a range of from 40° to 100° Fahr., which if the calibration were effected at 70° Fahr. means a variable error of 6 per cent, which cannot properly be designated as falling within allowable limits. If the shunt be made of copper so that its resistance increases in the same ratio as that of the instrument, the ratio of the two thus remaining the same, we encounter the fact that instruments and their shunts are very seldom of the same temperature, the former being usually on the front of a switchboard where the temperature may be taken, as about 80 degrees on an average, and the latter, in the rear surrounded by current-carrying conductors, rheostats, and the like, often boxed in so as to be at a temperature of 120° Fahr., or more. This would mean an error of 8 per cent if the instrument and shunt were calibrated at the same temperature. It would not be safe to assume that the shunt will always be at a point where the temperature is higher than that at which the instrument is located, either, as it is not uncommon to find switchboards erected in galleries where their rears, and hence the shunts mounted thereon, are exposed to direct blasts from open windows in winter, their fronts, where the instruments themselves are located, being at the same time subjected to the hot air of the interior of the station. The compromise that leads to the minimum value of the greatest error possible under these varying conditions is to make the shunt of a material having a temperature coefficient one half of that of the instrument circuit formed by the instrument windings with the attached flexible leads. The error is in this way halved, but even then we have possible variations of 3 or 4 per cent from the normal from this one cause alone, a figure which, while it would have no earthly effect on the operation of 99 per cent of the plants in existence, would, if known, be protested against in holy horror by the majority of the operators who have heard tales of accuracies of one half or even one fifth of a per cent for so long that they actually expect to be able to count on this being attained in ordinary practice.

Another very common source of error in shunted ammeters is the resistance at the point of contact where the shunt leads are attached to the instrument and the shunt. For convenience in constructing the switchboard the leads are usually made detached from both instrument and shunt, and the connections are finally completed by securing the lead ends under screw heads and washers at each end, making a total of four of such joints. Now, metallic surfaces become corroded and screws often work loose where there is vibration, with the result that such joints become of very uncertain resistance and the instrument readings are correspondingly thrown out. Cases have frequently come to the notice of the author in which brightening the surfaces and retightening the screws has caused a difference of 25 per cent or more in the indications with the same load. Such errors can obviously be minimized by careful periodic inspection of the contacts, and where such instruments are installed this practice should be faithfully followed.

The error pointed out on page 89, due to leading the current into and out of the shunt at a different set of points than those used when calibration was effected, seldom enters as a considerable factor with well-built switchboards, but the errors due to thermo E.M.F.'s, mentioned on page 90, may be larger than good practice will permit. One manufacturer avoids the difficulty by the expedient mentioned on the page referred to, that is to say, by placing the points of attachment of the shunt leads inside of the distribution terminals of the shunt.

Another uses the following special plan:

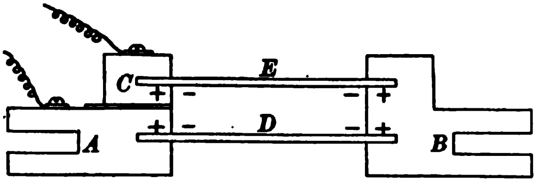

FIG. 124.

Referring to Fig. 124, *A* and *B* are the shunt terminals, *D* the resistance strip, made of a different metal from the terminals, *E*, a conductor, of the same material as *D* and *C*, a terminal of the same material as *A*, secured to *A* in such a manner that the thermal contact is good, but the two are electrically insulated. If, now, the block *B* is at a higher temperature than the block *A*, due, for instance, to a poorer contact between *B* and its bus-bar, there will be a lesser thermo electric E.M.F. at the junction between *A* and *D* than at the junction between *B* and *D*, and if the values of these E.M.F.'s are 1 millivolt and 2 millivolts respectively, there would be a difference of potential of 1 millivolt between *A* and *B*, due to that cause alone which would be added to or subtracted from that due to the drop in potential across the shunt terminals because of the current flowing through it, and would hence introduce a corresponding error in the indications of the instrument if the leads were attached at these points. If, however, one instrument lead is attached to *A*, and the other to *C*, as shown in the figure, the equal and opposing E.M.F.'s at the junctions between *A* and *D* and *C* and *E* cancel one another, and the E.M.F. between *A* and *C*, being then that due to the drop of potential because of the current flowing only, thus becomes in direct proportion to the current strength. A shunt of this kind is illustrated in Fig. 125.

Ammeters for Both Direct and Alternating Current.

THE KELVIN AMPERE BALANCE.

As was pointed out in the chapter on laboratory standards for the measurement of current, the Kelvin ampere balance works equally well, whether the current be direct or alternating, as, in the latter event, the current in the various coils reverses simultaneously and the resultant effort is always to urge one end of the balance up and the other down.

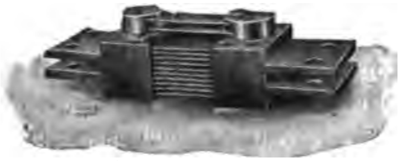

Fig. 125.

This instrument, however, hardly belongs in the class of apparatus for the commercial measurement of current strengths as its bulk, weight, and cost, the length of time required to obtain a reading, and the fact that it is not direct reading, render it unsuited for all except laboratory work.

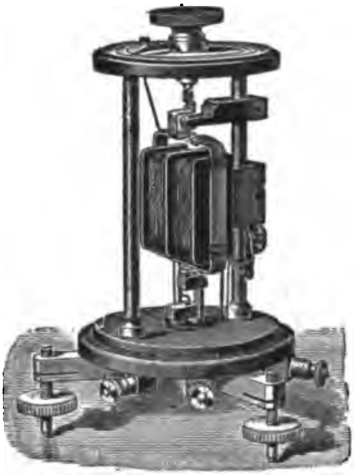

Fig. 126.

SIEMENS' DYNAMOMETER.

This familiar instrument, illustrated in Fig. 126, consists of two conductors, each wound into coil form, one of them being stationary and surrounded by the other, their axes being in line, but their planes at right angles. The outer coil is suspended by a fine silken fiber or a steel pivot resting on a jewel bearing, and has secured to its upper side one end of a spiral spring whose other extremity is made fast to what is called a "torsion head." This torsion head is a button which can be manually rotated about its axis and which carries a pointer that sweeps over a scale divided into degrees. Attached to the outer coil itself there is another pointer coming up to the same scale, but whose motion is limited by two closely adjacent stops. Current is conducted to and from the outer coil, through mercury cups secured to the frame of the apparatus, and the electrical connections between the two coils are usually so made that the current to be measured has to flow first through one and then through the other, they being connected in series. When current flows in this way, the suspended coil tends to turn so that its plane is parallel to that of the stationary coil, something that is not possible because of the stops which limit the play of the so-called zero needle attached to it. To bring the zero needle back to the position from which it started, and which is generally called the zero mark, the knurled button secured to the spring is rotated until coincidence is shown. The torsion spring is now subject to a stress which is equal to the reaction between the fixed and moving coils, and the amount of the said stress, as indicated by the pointer attached to the torsion head and showing the amount that the spring has been wound up, gives the current strength, as each apparatus is provided with a set of curve sheets, from which the ampere value corresponding to any scale degree may be read off.

The Siemens instrument can be made more permanent, so far as its accuracy is concerned, than the direct current devices before described, as the uncertain element of the strength of the permanent magnet entering into the construction of the D.C. instruments is eliminated and, as the single spring does not carry current, there is no danger of having its elasticity modified by being overheated from that cause. On the other hand, the mercury contacts are a nuisance, as the cups must be drained before the instrument can be transported, and the constant reference from scale reading to curve and back to notebook is very trying, when numerous observations are to be made. They also share the same objection to which a large majority of alternating current instruments are open, that is, that the field furnished by the stationary coil is but weak, and neighboring fields may form a considerable percentage thereof. This makes no difference when alternating currents are being measured, as what the foreign field adds to the instrument coil field when current flows in one direction, is subtracted when the current flow reverses. When measuring direct current, however, this favorable condition does not exist, and if accurate results are to be had, it is necessary to pass the current through the instrument first in one direction, noting results, and then, with the minimum possible delay, reversing the connections and noting the new result. The true value may safely be taken as the arithmetical mean, namely, one half the sum of the two observations.

ELECTROMAGNETIC INSTRUMENTS.

Kohlrausch Instruments.

One of the earliest, if not the earliest, form of electrical measuring instruments is that in which the current to be measured is passed through a hollow coil of wire, that is, a solenoid, and its force measured by the attraction exerted on a magnetic body suspended within the core. The simplest example of such an instrument is the Kohlrausch, shown in Fig. 127. The solenoid in this instrument surrounds a long thin iron wire which is suspended from above by a coiled spring similar to that in the ordinary spring balance. A pointer secured to the iron wire, or a prolongation thereof, moves vertically over a scale, empirically graduated to show current strengths. Such an instrument will work, whether the current flowing through the solenoid be direct or alternating, but care must be used in the design if accurate results are to be attained when the instrument is used with both kinds of current, because if the iron be hard, or of too large a mass, the indica-

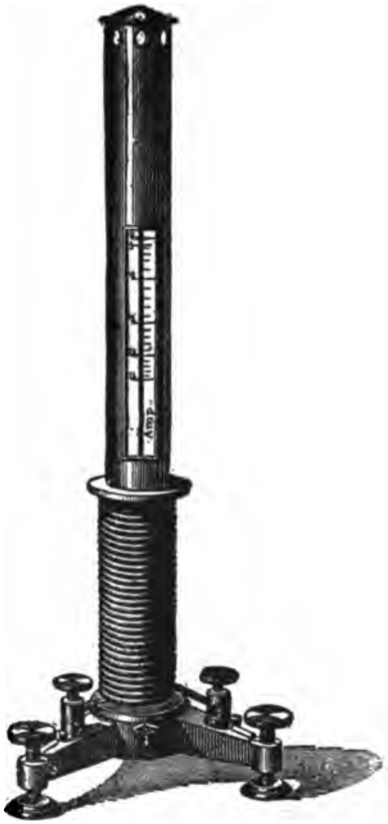

FIG. 127.

tions will not be correct for both, unless separate scales be drawn. For ammeters, the best design calls for the use of a very fine iron wire for the moving element, as this eliminates to a great degree the error due to varying frequencies, and also has the advantage of making the scale of more convenient divisions. The latter holds good, because of the fact that the attraction of a solenoid on an iron core varies as the square of the strength of the current until the core is magnetically saturated, after which time the attraction becomes directly proportionate to the current strength. With a very small core, therefore, the part of the scale in which the divisions are of unequal width is a very small one, in fact, it is possible so to design the apparatus that, from 10 per cent of full capacity upward, the scale divisions will be practically equally spaced for equal current increments.

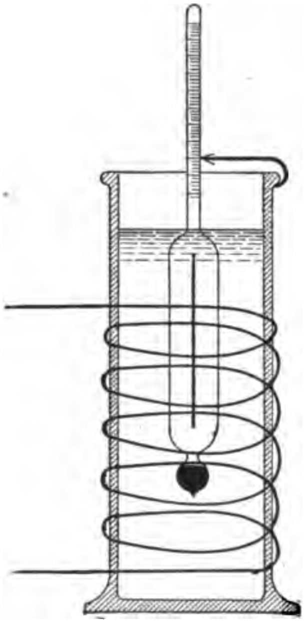

FIG. 128

In voltmeters, the iron core is usually made more massive, in order that the law of squares may hold good throughout a good part of the range, as this gives more open divisions at the part of the scale where readings are usually taken.

Atkinson Instrument.

The Kohlrausch electromagnetic instruments are not in common use in this country, but find their greatest popularity on the continent of Europe. In England a modification thereof is used to a limited extent. The instrument referred to is the "Atkinson," diagrammatically illustrated in Fig. 128. In this the solenoid surrounds a vessel containing a fluid in which floats a sealed hollow glass cylinder with a graduated stem, very similar to a hydrometer. The iron wire is placed inside of this float, so that the pull exerted by the current flowing through the solenoid is against the buoyant effect of the liquid on the more or less submerged float, instead of a coiled spring. This modified Kohlrausch instrument gives indications that are much more "dead beat" than those of the original form, but this is at the expense of simplicity and portability.

One of the best, and to-day most widely used forms of electromagnetic ammeters, retains the feature of a very fine iron wire suspended in the center of a current carrying solenoid, but instead of having the extent of motion of this wire indicate directly the current values, the motion is first translated into that of a pivoted pointer that swings over a graduated circle arc.

Fig. 129 shows the construction of such an instrument. The iron wire is suspended from an arm rigidly secured to an axle whose ends are pointed and rest in jewel bearings, and the same axle carries a pointer and a weight, *W*, which, as the needle moves, offers an increased resistance to its displacement. The figure is so nearly self-explanatory that it is needless to go into the construction at further length.

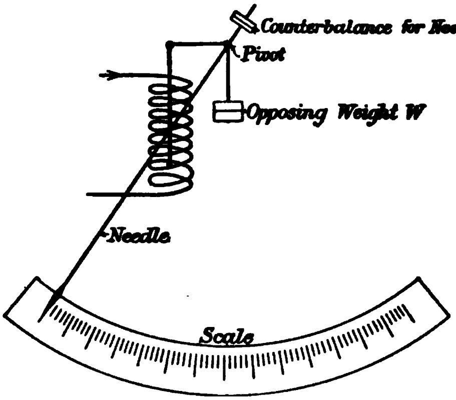

FIG. 129.

If the swings of the needle of electromagnetic instruments like this be damped, either by a suitable air vane moving in a nearly closed box, or by a piston fitting very loosely in an open ended cylinder nearly filled with viscous oil, we have a form of apparatus that is exceptionally well suited for use on a switchboard of an industrial plant. The accuracy can be made more than sufficient for commercial purposes, by proper design and careful selection of the iron; moreover, there are no parts liable to change through age, the force opposing the needle's swing being that due to gravitational attraction, and there being no springs or permanent magnets. Furthermore, the apparatus is available for either direct or alternating current.

Kelvin Ampere Gauges.

Lord Kelvin, one of our foremost authorities on matters pertaining to electrical measurements and electrical measuring apparatus, has, within the last few years, put the seal of his approval on instruments of this class, by redesigning and putting on the market, under his name, the Kelvin ampere gauges, one of which is shown in Fig. 130. As may be seen from this illustration, the dead beating is effected by an oil damper, the movable element is supported on hooks which allow of a rolling motion, and the opposing force is that of gravity. The extreme reliability of these instruments has led to their wide adoption abroad, and the author expects to see similar types extensively used in this country before the lapse of many years. The station engineer will be far better satisfied with an ammeter that is accurate to only one or one and a half per cent, when installed, but which will retain that accuracy unchanged for an indefinite period, than with a meter of a questionable quarter or half per cent error on erection, that may become an unknown amount greater in the course of a few months, because of magnet or spring strength changes, varying lead resistances, etc. The accuracy of a solenoid ammeter is, moreover, for all practical purposes, absolutely independent of temperature, whereas shunted ammeters

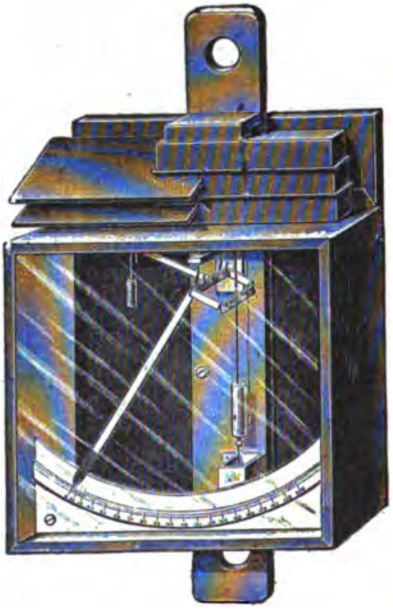

FIG. 130.

may, as before explained, have temperature errors that may be as great as 1 per cent for a change of 5 degrees.

In large capacities, solenoid ammeters are not inexpensive, as the construction of a coil, even of but one or two turns, to carry heavy currents is a costly matter. They are, also, expensive to install, as it is, of course, necessary to pass the entire current to be measured through the meter, and this means extensions and complicated rearrangements of heavy copper busbars.

To meet this last objection, Lord Kelvin places the solenoid with its accompanying core on the bus bars themselves, and runs a light cord from the core to an arm actuating the swinging needle, enclosed in a conventional case and swinging over the usual graduated scale. In such case it is necessary that the indicating portion of the instrument be located vertically above the actuating part, but the indicating portion is still free to assume any form, usually either the type shown in Fig. 130, or the so-called edgewise type, shown in Fig. 131.

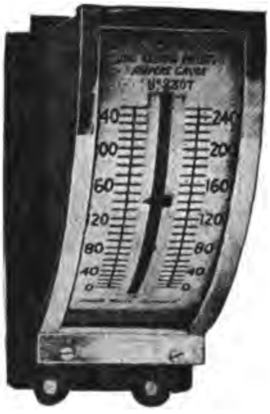

FIG. 131.

Thomson Inclined Coil Instruments.

The Thomson inclined coil ammeter is an electromagnetic instrument extensively used in this country for the measurement of relatively small currents. In it, as will be seen from Fig. 132, the stationary coil of wire is placed at an angle to the

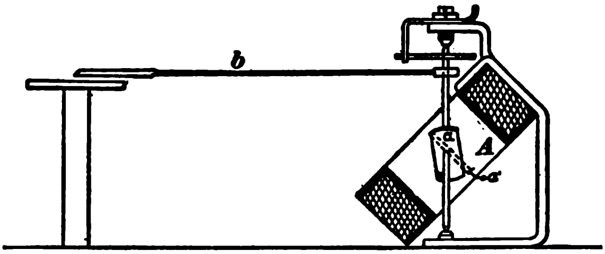

FIG. 132.

axis of the staff of the indicating needle and the staff carries a strip, or bundle of strips, of iron, which, when no current is passing, are held so that their plane is nearly parallel to the plane of the coil. When current is put on, the bundle of strips, of course, tends to take up a position such that the reluctance of the magnetic circuit of the solenoid is reduced to a minimum, and in so doing, of necessity rotates the iron and with it the shaft to the position shown by the dotted line. The force with which it tends to rotate is in proportion to the current strength, so that the amount that it winds up the volute phosphor bronze spring which opposes its motion, as indicated by the attached needle, indicates the current strength. The arrangement of parts in this instrument results in a large angular motion of the needle, without necessitating the use of any multiplying devices, such as levers, gears, or pulleys. When properly designed and built, this instrument is capable of a very satisfactory degree of accuracy and reliability.

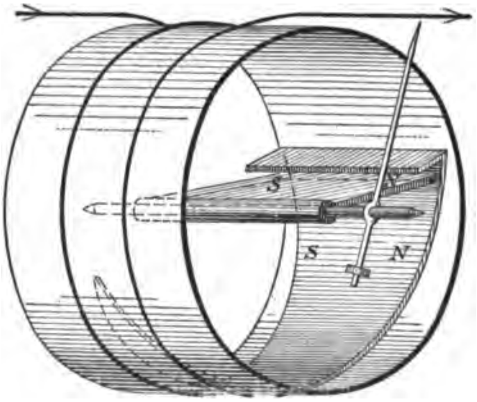

FIG. 133.

Magnetic Vane Instruments.

Another form of electromagnetic ammeter, called the "magnetic vane type," and in extensive use in this country, is diagrammatically shown in Fig. 133. Here the current passes through a solenoid, whose axis is at right angles to the face of the instrument.

Permanently secured inside of the solenoid spool is a strip of soft iron which when unrolled is triangular in shape, the base of the triangle being bent out at right angles, as the figure shows. Also within the solenoid core is a steel staff or shaft whose pointed ends rest in appropriate jewel bearings, and which carries, in addition to the indicating needle, a flat rectangular strip of soft iron, which is parallel to the bent in stationary piece when no current is on.

When current passes through the wire coil, the stationary and movable strips are, of course, similarly magnetized, so that the like poles of the magnets so formed are adjacent; they therefore repel each other, and in so doing the movable one carries with it over the scale the indicating needle.

This form of instrument has many modifications, differing in more or less important details. The force opposing the motion of the needle is sometimes that offered by a flat spiral spring, and sometimes the attraction of gravity on a weighted arm. Like other electromagnetic instruments, this type is operative with either direct or alternating current, and its motions are damped, preferably, by means of the air vane or the oil dash pot.

Electromagnetic instruments in which a portion of the iron used is stationary, are open to certain objections, experiment showing that there are errors, when a fixed plate of magnetic material is present, that exist to a much less extent when such a plate is not used. This error is mainly due to the following cause: Referring to the chapter on magnetic hysteresis (see page 380), the flux through a magnetic circuit, composed wholly of iron, has different values for the same magnetizing force, according to whether the magnetizing force be increasing or decreasing.

When, on the other hand, the iron is removed, the flux is the same, no matter how any given current value has been reached, that is to say, air is non-hysteretic. In a composite magnetic circuit, formed partly of air and partly of iron, such as that in the instruments in question, the hysteretic influence of the iron decreases as the percentage of the total magnetic circuit formed by the iron decreases. In the magnetic vane type of instrument, therefore, involving stationary as well as movable iron, the error due to hysteresis is thus increased, so that there is a greater discrepancy between the values of a rising and falling current of the same strength.

The character of the iron entering into the construction of all electromagnetic instruments is of great importance, as the hysteresis losses vary widely in different specimens of the metal. While careful design and a proper selection of the iron may result in an instrument in which the difference in indications between a rising and falling current of the same strength is no greater than one half of one per cent, poor design and poor iron may cause an error of 5 per cent, or over. It is advisable, therefore, carefully to test electromagnetic instruments intended for use in direct current work, before assuming that they are correct and, moreover, to repeat the checking at intervals, because iron ages magnetically, and has a higher hysteretic coefficient, after being subject to changes in the intensity of its magnetization for extended periods. The effect of aging is negligible in some brands of iron, and can be reduced in all by proper preliminary treatment, although this fact does not seem to be appreciated by all instrument makers. Where electromagnetic instruments are used for the measurement of alternating currents, the first source of error, namely, the difference in indications between a rising and a falling current, does not exist, by reason of the continuous, automatic reversal that is going on and which was present when calibration was effected.

HOT WIRE INSTRUMENTS.

When an electric current flows through a conductor, the energy expended in overcoming the conductor's resistance is manifested in the form of heat. The energy consumed varies as the square of the current strength, and the temperature varies proportionately, so that, as a body brought to different temperatures expands and contracts, these variations, suitably indicated, may be utilized as a means of measuring current strengths.

The amount of elongation of a heated conductor depends on the temperature rise, the length of the rod or wire, and the material of which it is composed.

Cardew Instruments.

In what is, perhaps, the earliest commercial form of hot wire instrument, namely, the Cardew, the conductor is a platinum silver wire, about seven feet in length, arranged as shown in

Fig. 135. It is coiled back and forth over ivory pulleys in order to decrease the length of the instrument, and the motion is amplified by a gear wheel and segment, or a pulley and cord, so that the needle traverses an arc of over three hundred degrees. To prevent air currents from cooling the wire, the whole is enclosed in a case, the wire and lower pulleys being shielded by a brass tube. As the coefficient of expansion of the brass tube and the platinum silver wire are not identical, it is evidently not feasible to attach the bearings for the pulleys over which the wire passes, to the tube, for, if this were done and the instrument placed where the temperature was not that which existed at the time when the instrument was calibrated, the difference between the expansion of the tube and that of the wire would cause the needle to move. The pulleys are, therefore, mounted on a framework built up on a combination of brass and iron rods, with the lengths of these respective metals so selected that the whole expands and contracts with changes of temperature at the same rate as the platinum silver wire. Fig. 136 shows the complete meter.

The Cardew instrument should not be used with the tube in a vertical position as air currents are then set up within it by the heated wire, and the cooling effect of these currents on other portions of the wire causes an appreciable error. The tube is, therefore, always placed horizontally, when possible.

While abundantly able to satisfy the requirements existing when it was devised, the Cardew instrument, as just described, does not compare favorably with modern hot wire types. The errors introduced by the friction of the bearings of the numerous wheels it contains, the disturbing effect of air currents set up in the tube by the heated wires, and the generally unsatisfactory result of leading a wire around the sharp bend of a pulley when the expansion of its whole

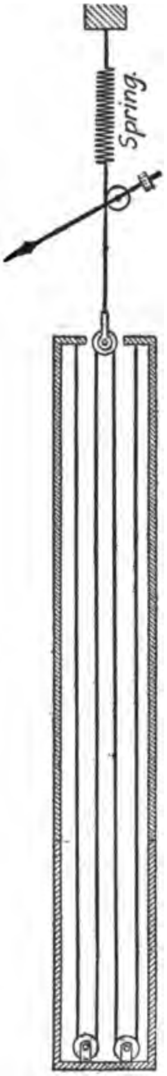

FIG. 135.

length is to be utilized, render its indications too inaccurate for present day demands. The electromagnetic and moving coil instruments that have been developed since its time are much better and, because but little work was done on apparatus utilizing the hot wire principle for a considerable period, the prevalence of these other forms has led many to believe that the principle itself is inherently defective. Such, however, is not the case, as hot wire measuring instruments when properly designed, are capable of making a showing that is fully satisfactory as compared with that of the other types.

Hartmann and Braun Instruments.

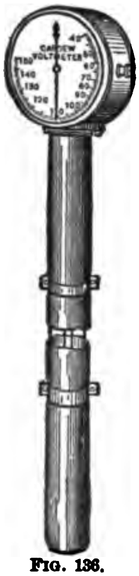

FIG. 136.

Not only is the length of the Cardew instrument objectionable, but the wire therein must be run at such high temperatures, in order to obtain a sufficient linear expansion to work the indicating gear, that the amount of energy consumed renders its use impossible for the measurement of small currents when the allowable drop in E.M.F. in the meter is small, or for very large currents where the potential necessary to force the current through the instrument is obtained from the drop across the terminals of a resistance placed in the main circuit, that is, it cannot be used as a shunt ammeter. The Hartmann and Braun hot wire instruments overcome these disadvantages, to a considerable degree, by the employment of a somewhat different principle. It is well known that, if a wire strand be stretched between two fixed points, the amount that it will sag at its center, when the strand is slightly stretched, is many times the elongation of the strand itself. Referring to Fig. 137, *AB* is the expansion wire in the Hartmann and Braun instrument, which, when current flows through it, stretches and allows its center to sag. At the center is attached one end of a wire, *CD*, secured to a fixed point at *D*. When the distance between *C* and *D* lessens, because of the sag of the hot wire, *CD* is itself pulled aside by the spring attached to its center, by an amount that is as much greater than the sag of *AB*, as the sag of *AB* is greater than the elongation of *AB*. At the point, *E*, in the center of *CD*, there is attached a cord, *G*, which passes around a pulley fastened on an axis carrying an indicating needle, and this cord is kept taut by the spring, *S*. In this way a very short hot wire elongates sufficiently with a reasonable rise in temperature to cause readily readable needle deflections. The terminals of the hot wire are attached to a common metallic framework, but are electrically insulated therefrom. The metal of the framework has the same coefficient of expansion as the wire, so that changes in the temperature of the surrounding atmosphere affect both equally, and do not give rise to erroneous indications. It is claimed that with a voltage as low as 300 millivolts at the terminals of conductors attached to *A* and *B*, sufficient current will flow through the wire to cause it to expand to an amount that will make the indicating needle traverse full scale. This drop is one that is readily attainable with a shunt whose size and cost are not prohibitive, and which does not call for an unreasonable drain of energy from the circuit. The end *A* of the expansion wire is secured to a special terminal part as shown. This is provided in order that the zero position of the needle may be adjusted by varying the tension of *AB*, should this at any time be necessary. A complete Hartmann and Braun hot wire type instrument of the kind made in this country is shown in Fig. 138. The device having the shape of a wheel with opposite segments indented, attached to the axis of the pointer, is of thin sheet aluminum, and moves between the pole faces of the permanent magnet,

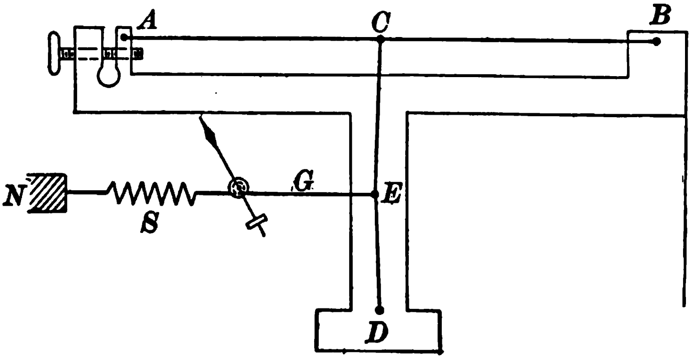

FIG. 137.

the eddy currents set up in the aluminum when the needle swings assisting in bringing it rapidly to rest and making the indications dead beat.

Roller Hot Wire Instruments.

The principle on which these instruments operate is diagrammatically shown in Fig. 139. Referring to it, a wire, *ab*, of high resistance, low temperature coefficient and non-oxidizable metal is secured at one end to a plate, *c*, passed around a pulley, *d*, secured to a shaft, *e*, and its free end brought back again and mechanically, though not electrically, attached to the same plate, *c*. Plate, *c*, is kept under stress by the spring, *f*, which constantly tends to pull it in a direction at right angles with the axis of the shaft, *e*, and is so guided that it can move in that one direction only. To the shaft, *e*, is likewise secured an arm, *g*, bifurcated at one end and counterweighted at the other. Between the extremities of the bifurcated ends of the arm, *g*, is another shaft, *h*, on which there is a small pulley and to which is attached the needle, *i*, that gives the desired indications; a a fine silk fiber is attached at one end to one of the arms of, *g*, then passes around the pulley and the staff, *h*, and finally has

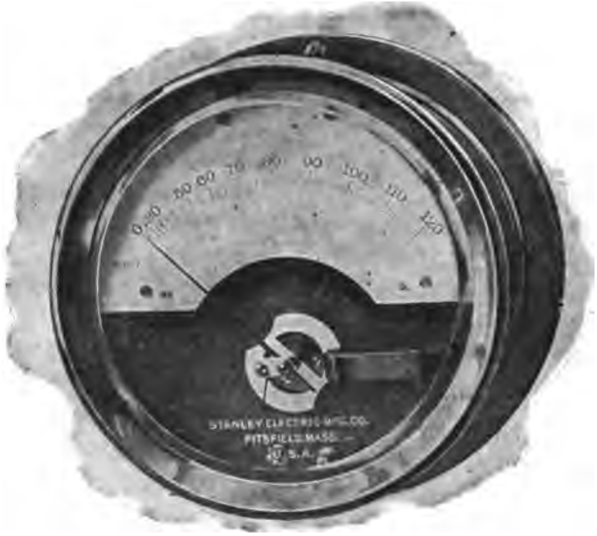

FIG. 138.

its other extremity secured to the other arm. The arms are springy and serve to keep the silk fiber taut. The current to be measured flows through the wire, *a*, only, entering and leaving as indicated by the arrows. Evidently, when *a* is heated by the passage of current, it expands, which, as *a* and *b* were originally under the same tension, makes *a*'s tension relatively less than that of *b*, and equilibrium can be restored only when the pulley, *d*, rotates sufficiently again to equalize the strain. The rotation of *d*, of course, carries *g* with it, and *g*, in moving, causes the silk fiber to rotate the shaft which carries the needle. If the temperature of the air surrounding the instrument changes, *a* and *b* are affected alike, and their resulting equal expansion simply results in a movement of the plate, *c*, back or forth in its path without any tendency to rotate the pulley.

Among the advantages of the above construction is the fact that the member which compensates for the expansion of the active wire, due to the temperature changes of the surrounding atmosphere, is not only of the same material as the expansion wire itself, but is actually a piece of the same wire, and hence, has exactly the same mass and physical characteristics. The compensation must, therefore, be perfect.

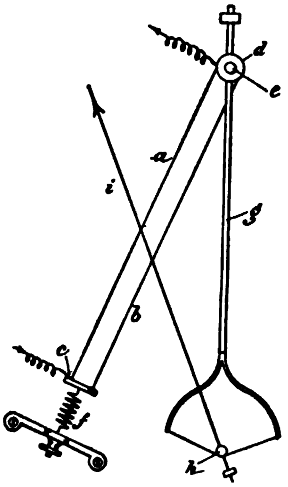

FIG. 139.

The entire moving system shown in Fig. 139 is mounted on a single base plate, free to rotate over a small angle round a heavy shaft secured to it immediately below and in line with shaft, *h*, around which the needle swings. This enables one to alter the position of the needle relative to the scale without interfering with any of the mechanism in any way. A complete instrument of this type is shown in Fig. 140.

ELECTROSTATIC AMMETERS.

An electrostatic instrument may theoretically be used for measuring current in connection with a shunt, just as current is measured with ammeters of the permanent magnet type as described on page 161. Owing, however, to the fact that electrostatic instruments require a considerable potential difference for their operation, and that such instruments must be of the fiber suspended instead of the pivot borne type, they can hardly be said to come under the head of commercial measuring apparatus, and are mentioned here, simply to keep the scheme of treatment intact. If, in special cases, a delicate electrostatic voltmeter be available, it, in connection with a shunt, evidently forms a means of measuring the strengths of either direct or alternating currents, but, in the latter case, care must be taken that the shunt across which the drop is measured has no self-induction, for, if this be present, the drop will be in excess of the *IR* drop, and the indications correspondingly greater than they should be.

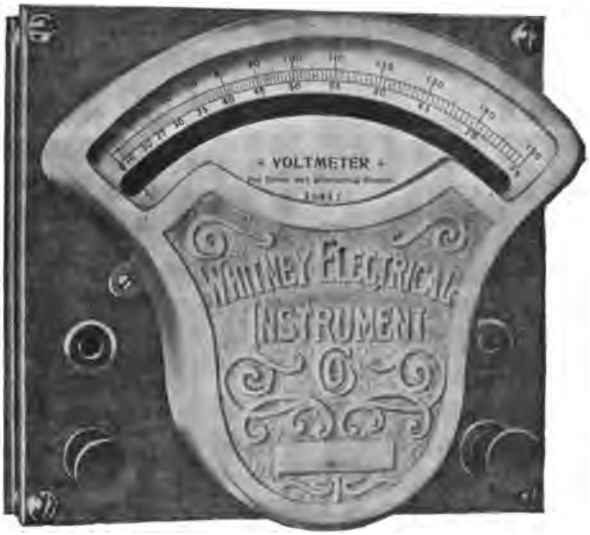

Fig. 140.

When used for alternating current measurements alone, the difference of potential necessary to operate the electrostatic meter may conveniently be made of much higher value by substituting for the simple shunt, a transformer, whose primary is inserted in the line as a shunt, and which is so designed that a rise in the strength of the current flowing through the primary winding causes a corresponding rise in the E.M.F. delivered by the secondary. The objection to this expedient is the fact that the accuracy is dependent on the frequency, and that the transformation ratio of the transformer is exceedingly high.

AMMETERS FOR ALTERNATING CURRENTS ONLY.

Induction Ammeters.

It is a well-known fact that, if a mass of conducting material be placed within the influence of two alternating magnetic fields which vary in intensity and direction at the same rate, but whose maxima and minima do not occur simultaneously, the reaction between the currents thus set up in the mass, and the magnetic fields respectively, will, if the former is suitably journaled, tend to set it in rotation. This principle may be utilized in various ways in the construction of alternating current instruments.

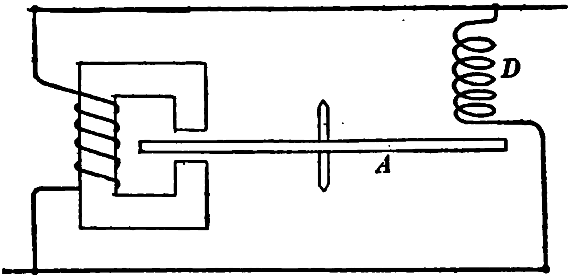

FIG. 141.

Referring to Fig. 141, if *A* be a disk of copper, or aluminum, one portion of which is embraced between the ends of a *C*-shaped structure of laminated iron, about one of whose legs wire is wound, and if *D* be another coil of wire without an iron core, and the two windings are connected to a source of current as shown, a torque tending to rotate the disk *A* is set up because the currents in the two coils are out of phase, owing to their different inductances. If the tendency of *A* to rotate under these conditions be opposed by a volute spring and a pointer be attached to the disk, the scale over which the pointer would play may then obviously be calibrated directly in units of current strength by comparison with suitable current standards.

The phase difference between the two alternating magnetic fields may, of course, be brought about in various ways. Fig. 142, for instance, shows a disk of conducting material arranged so as to be rotatable between the jaws of a *C*-shaped structure of laminated iron. The structure has a hood of conducting but non-magnetic material let into the ends of the *C*, extending over a portion of the faces so that the currents set up therein distort the magnetic field at that point, and, in turn, exert a force tending to cause the disk to rotate in well-known "shading coil" fashion. As in the preceding instrument, the extent to which the disk, or the pointer thereto attached, rotates over a fixed scale, may be used as a measure of the current strength.

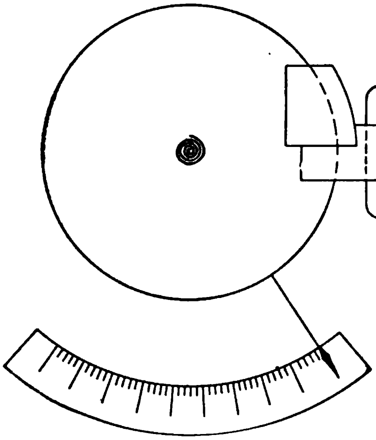

FIG. 142.

In both of the instruments just described, it is convenient to damp the movement of the disk and render the indications of the apparatus dead beat by arranging a permanent magnet so that the disk may rotate between its polar extremities, and which, therefore, acts as a magnetic brake. Likewise, both must be calibrated for the frequency on which they are to be used, as the torque is dependent thereon, and both are subject to marked errors when exposed to varying temperatures because of the high temperature coefficient of the material of which the rotating elements are necessarily made.

Induction types of instruments are in fairly extended use in this country, but it can hardly be said that their results are dazzlingly accurate or satisfactory as compared with those of a good iron core solenoid device.

SERIES TRANSFORMERS.

Owing to the relatively large energy consumption of alternating current ammeters of the electromagnetic and induction types, and to certain other reasons to be explained further on, it is not usual to employ shunts to furnish the drop necessary to actuate them, but to install instead transformers whose primary windings are connected in series with the supply line, the secondary terminals being attached to the instrument. This is convenient when heavy currents are to be measured, as it obviates the necessity of winding the instrument with wire heavy enough to carry the total current and the expense that is frequently involved for the conductors that convey the current to and from the instrument. It is also of value where the measured current is supplied under high potentials dangerous to human life, as the insulation between the two windings of the transformer may be made to withstand any desired voltage so that that of the current passed through the meter is perfectly innocuous.

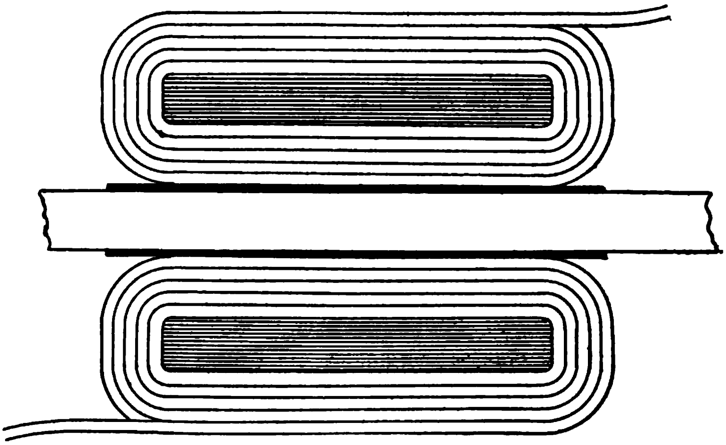

FIG. 143.

Series transformers must be designed so that the ratio of the currents in their two windings remains practically the same at any load, differing in that respect from the ordinary lighting transformers where the potential ratio is the one that it is desired to keep constant. Typical forms are shown in Figs. 143, 144, and 145, perspective and cross-sectional views being given. The transformer in the first figure is of the cable type in which the primary winding is a straight section of the conductor carrying the current to be measured, while the secondary winding is formed of several turns of finer wire laid parallel to it. In the second form of transformer, the primary winding incloses the secondary, while in the third, the structure is similar to that of the ordinary lighting transformer, but instead of having the primary windings make several turns about one side of the iron core, it passes straight through it, being thus in effect a half turn, although this is, of course, completed to make a full turn by the return circuit from the load as formed by the other bus-bar. All have a transformation ratio that varies somewhat with the varying frequencies, and hence, all must be calibrated for the number of alterations on which they are to be used.

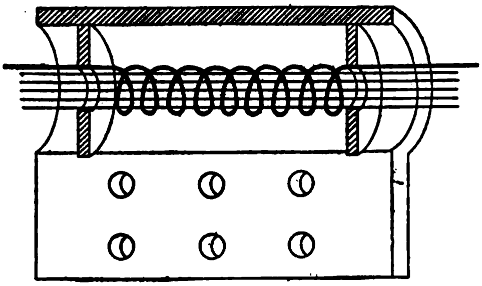

FIG. 144.

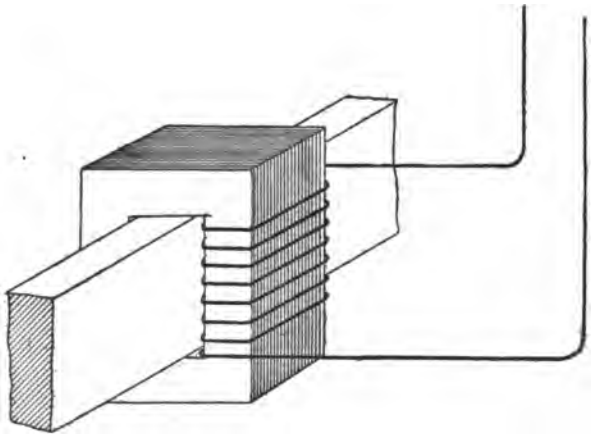

FIG. 145.

SHUNTS FOR ALTERNATING CURRENT INSTRUMENTS.

As mentioned above, shunts are sometimes used in connection with alternating current ammeters, this being done when there is no necessity for interposing a high insulation between the instrument winding and the current carrying conductors, and when the instrument is of a type sufficiently sensitive to be actuated by the drop across a shunt of commercial dimensions. As instruments sufficiently sensitive to use on these drops are usually of the hot wire pattern in which the inductance is low, it is a matter of small difficulty to make the design such that the ratio of the inductance to the resistance of the shunt and the instrument are equal so that the frequency of the current being measured introduces no error, and the apparatus may be used on either direct or alternating current without its being necessary to employ correction factors, or draw in additional scales.

Very particular care must, however, be taken to make the resistance of the joints between the instrument terminals and the shunt a minimum, as the instrument circuit resistance is already low, and if that of the joints is comparable thereto, an error is introduced.

CALIBRATION OF AMMETERS.

SOURCE OF CURRENT.

In calibrating an ammeter, the first matter to consider is the source from which the testing current may be drawn. In all cases, it is desirable to have this source of low potential, as otherwise it is necessary to employ bulky and expensive auxiliary apparatus, such as rheostats or other resistances, across which the portion of E.M.F. not required to force the current through the instrument may be dropped. For the calibration of direct current instruments, this means that the most suitable current source is either a low voltage dynamo, such as is used for electroplating work, or else one or two large storage battery cells. The electroplating dynamo is convenient when a source of power maintaining a steady speed is available, because the

E.M.F. which it generates, and hence, the current which it will force through the instrument under test, is very easily regulated by means of an inexpensive rheostat placed in its field circuit. Unfortunately, however, plating dynamos are not commonly at hand, or, if one is, the speed of the pulley that drives it may be so irregular that the current cannot be held steady for a sufficient length of time to make the necessary observations. A storage battery, therefore, forms the source most commonly used, and has the great advantage, that for the short periods of time during which current is being drawn in making comparisons between the tested instrument and the standard, it will deliver a current considerably in excess of its normal discharge rate without injury.

When testing alternating current ammeters, the current source may be any alternating current dynamo, as the potential at which current is delivered may readily be stepped down by means of a transformer, to any suitable figure, the current strength at the same time being raised to a correspondingly higher value. Adjustable impedances are then employed to vary the amperage over the range needed in the checking of the particular instrument under test.

CURRENT REGULATING DEVICES.

In order to be able to adjust the strength of the current passed through the instrument under test, and to hold it constant at any desired point for a reasonable length of time, it is usual to employ resistances whose construction varies somewhat, according to whether the currents are large or small. In the latter event, common wire resistances or rheostats of any conventional form are employed, it being advisable to select those in which the resistance wire is of a metal having a very small temperature coefficient, so that, when it is heated by the passage of current, its resistance may not change sufficiently to necessitate a constant readjustment. Such rheostats are usually provided with contact plates, so it is possible to get only as many different current strengths as there are contacts. Sometimes, however, the resistance wires, or bars, are arranged so as to be accessible throughout their length and a sliding contact provided with a clamp is fitted to them; so that good contact may be made at any desired point, and hence, gives an infinite number of steps.

Another form of rheostat, whose resistance may be varied by imperceptible gradations, is built up of carbon, which may be in the form of carbon grains contained within an elastic envelope, capable of being compressed, to a greater or less extent, between a fixed terminal plate and a movable one. A rheostat of this kind is shown in Fig. 146. Where the currents are heavier, carbon rheostats are made by placing the broad faces of a number of carbon blocks in contact with one another, and enclosing them in a framework that is equipped with a screw, by means of which they may be pressed together more or less firmly. The greater the pressure, the less the resistance. A rheostat of this kind is shown in Fig. 147.

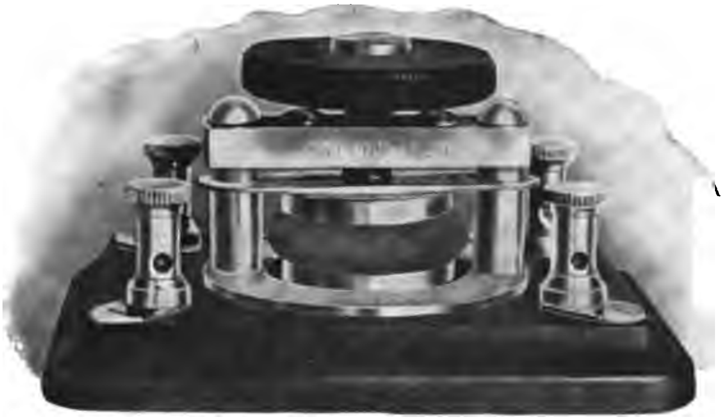

FIG. 146.

Plain (not coppered) arc light carbons may be used to make a temporary rheostat along the same lines by placing them on end in an asbestos-lined perforated bottomed box, as shown in Fig. 148. The two ends of the box are provided with large terminal sheets of brass, one of which can be pushed inward by turning the crank handle shown. The large radiating surface left by the interstices between the carbon rods enables this rheostat to carry comparatively heavy currents, but, in common with the two preceding forms, it labors under the disadvantage that the possible range of variation in resistance is rather small.

For laboratory work in handling heavy currents, a very convenient form of resistance is made up of German silver tubing through which a stream of water from the city mains is constantly flowing. The direction of the water flow should be from the lower to the upper part of such a tube in order to do away with the chance of having the tube fused if the water supply should momentarily fail. By using this artificial cooling method, there can be carried from fifteen to twenty times the amount of current that would be possible without it. The plan does not introduce difficulties because of the grounding of the current source through the stream of water which flows from the city mains if a few feet of rubber tubing are interposed between the mains and the German silver, as the resistance of a column of water of that length renders impossible the passage of any appreciable amount of current with the E.M.F.'s usually available in ammeter testing.

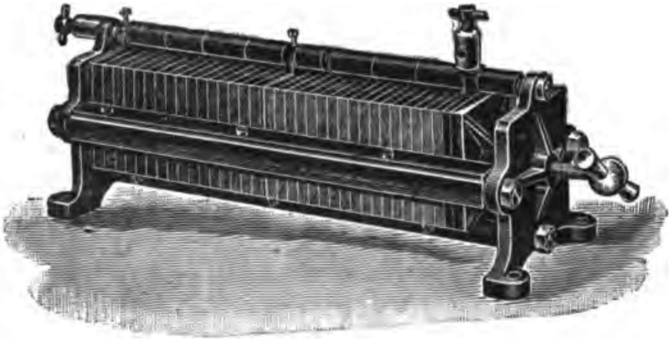

FIG. 147.

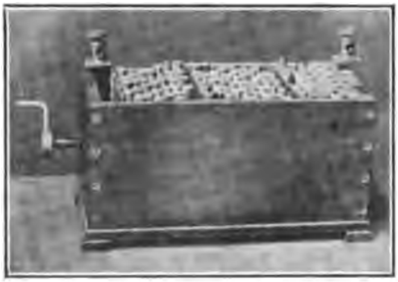

FIG. 148.

The current supplied for testing alternating current ammeters may, of course, be regulated by the same devices used for direct current. Where many alternating instruments are to be calibrated, however, it is cheaper to effect the regulation either by means of leads tapped out from the primary windings of a transformer from which the current supply is drawn, and in this way varying the ampere turns of the primary, or, better still, by introducing in the primary circuit an adjustable inductance or "kicking coil" such as is used for alternating current theater dimmers.

METHODS OF CALIBRATION OF AMMETERS.

Voltameter Method.

In spite of the fact that the value of an ampere is defined by the International Congress in terms of the performance of a silver voltameter, neither this nor the more easily used copper voltameter is commonly employed in the calibration of ammeters owing to the cumbersome nature of the voltameter itself and to the numerous precautions that must be taken to avoid the errors which may creep in, due to inaccurate observation of elapsed time, error in weighing the plates, and the necessity of maintaining the current strength absolutely uniform for many minutes. The method is, further, a very slow one; so that, while it may be used in laboratories for the calibration of secondary standards, it is out of the question to employ it commercially in testing a number of instruments. The standards ordinarily used are, hence, either of the secondary class, which must initially be graduated by comparison with a primary instrument, but which are so constructed that they contain no parts liable to change with lapse of time, or one like the potentiometer, giving ampere values derived from standards of resistance and E.M.F.

In both cases the apparatus shows the instantaneous values of the test current, and not the product of its mean value by elapsed time.

Calibrating with a Balance or a Dynamometer.

The secondary standard is usually either an ampere balance of the Kelvin type described on page 18 or a Siemens Dynamometer as described on page 165. The former gives closer readings, because of its great scale length; and it is less likely to change, since only its geometrical dimensions, the value of gravitational attraction, and the integrity of its windings can affect its indication, when properly installed. The dynamometer employs spring torsion instead of gravity for an opposing force, and spring elasticity may change. These springs are, however, made so long and worked so far within their limits of elasticity that an error due to a sudden change in that quality is extremely improbable. While their scale length is less than that of a balance, they are more portable, less care need be taken to obtain a vibrationless foundation, and readings may be taken with much greater rapidity. The results are, with ordinary care, sufficiently accurate for all commercial purposes.

Calibration with a Potentiometer.

The chapter on the potentiometer has explained how this instrument may be used as a standard in the measurement of direct currents. Giving, as it does, results in terms of the E.M.F. of a standard cell, and dependent only on this and the accuracy of the standard resistance across which the drops are measured, the results obtainable with a potentiometer are thoroughly trustworthy, if reasonable care be employed. By having a set of two or three standard resistances, and of two or three standard cells, all of which may be checked against one another, it is almost inconceivable that errors greater than those introduced by the inherent limitations of the apparatus could enter, particularly as the method is a zero one, and does not depend upon the constancy of the indications of any current actuated device. The potentiometer is always to be preferred for checking direct current ammeters if one is available.

Calibration of Alternating Current Ammeters.

An alternating current ammeter measures effective current strengths, that is to say, when it indicates a given number of amperes flowing from an alternating current source, it means that that current in flowing through a given circuit would expend therein the same amount of energy that a continuous current of the same amperage would expend in flowing through the same circuit and doing the same amount of work.

A hot wire type ammeter, therefore, in which the energy is expended in heating a resistance wire, after being calibrated with continuous current, may be used to measure alternating current amperes, and as a secondary standard for the calibration of other alternating current instruments. In a similar manner the electro-dynamometer and the Kelvin balance, in which the current energy is expended in keeping a spring stressed, or sustaining a weight against the attractive force of gravity respectively, after being first calibrated with continuous currents, may be used to standardize other instruments for the measurement of alternating current amperes.

When using the hot wire type of meter for a transfer standard of this nature, it is desirable to check its calibration with direct current, both immediately before and immediately after the measurement, as most designs have the unfortunate characteristic of lack of constancy of accuracy, so that confidence in their indications can only be obtained as outlined. With the dynamometer patterns of meters the calibration is more stable, but the conductors to and from them must be twisted together to form a cable, in order to avoid inductive influences, and their windings must be finally laminated in order that the distribution of current through them may be the same, whether that current be direct or alternating.

Precautions.

If the ammeter under test be of the electromagnetic type, errors due to changes in its temperature do not enter to an appreciable extent, since the number of turns of the actuating solenoid remains constant, and the whole current flowing through this influences the iron core to the same extent, whether the resistance of the windings be high because of a high temperature, or low because of a low one. Thus, the only effect of varying temperature is to cause a varying drop across the instrument terminals.

On the other hand, electromagnetic instruments work by magnetic attraction on iron, and the property of iron, known as hysteresis, by virtue of which the flow of the lines of force through it is dependent, not on the magnetizing force alone, but also on the magnetic stress to which it was previously subject, introduces an error. If the attractive magnetic force is attained by increasing the strength of an already existing current to a given new value, the pull on the iron core of the instrument is less than if the same value were reached by decreasing a larger current to that amount, and the instrument needle, therefore, has different positions to indicate the same current strength. The amount of difference depends on the design of the apparatus and the quality of the iron employed and is very small in good instruments. In others, however, the error is large, and it is, therefore, necessary, in checking the calibration of an electromagnetic ammeter, to make two sets of observations, one with an increasing, and the other with a decreasing, series of values to fully determine its characteristics.

If the ammeter to be tested be of the d'Arsonval type, in which there is a stationary permanent magnet, and a moving coil of wire which carries a known fraction of the current to be measured, this particular source of error is not present, since the wire is non-magnetic and non-hysteretic. On the other hand, temperature influences enter, since the materials entering into the composition of the two branches of the circuit, formed by the instrument and its shunt respectively, are different, and their temperature coefficients differ likewise; so, when the temperature is other than that at which the calibration was initially effected, the ratio of the currents flowing through the two, changes. This matter has been treated more fully in the section on shunts (see page 162) to which reference should be made. For work of high accuracy with d'Arsonval instruments it is preferable to have a shunt with a zero temperature coefficient and an instrument whose variation of resistance with variations of temperature is known, as appropriate corrections for the instrument temperature can then readily be applied.

CHAPTER VII.

MEASUREMENT OF POTENTIALS.

DIRECT CURRENT E.M.F.'S.

MEASUREMENT WITH THE POTENTIOMETER.

THE paragraph on the potentiometer (page 73) has explained how this apparatus is used in measuring an E.M.F. in terms of the difference of potential existing between the terminals of a standard cell. While it is not necessary to enlarge further on the apparatus here, it may be reiterated that this method is capable of the highest commercial accuracy and involves the use of apparatus that is comparatively inexpensive and exceedingly reliable.

MEASUREMENT WITH PERMANENT MAGNET VOLTMETERS.

All indicating voltmeters, with the exception of those of the electrostatic type to be treated further on, are nothing but ammeters of very high resistance and capable of measuring only minute currents. That such an ammeter can be calibrated to indicate voltage instead of amperage is evident from a consideration of Ohm's law, $I = \frac{E}{R}$. If in this formula R is a constant quantity and of a value so high that the I drawn from the circuit does not disturb the potential difference, E, at the points of attachment of the meter's terminals, E becomes directly proportional to I, and a given ammeter may, therefore, be calibrated in volts instead of amperes. This general remark should not be interpreted to mean that an indicating voltmeter is built exactly like an indicating ammeter; on the contrary, the requirements are diametrically opposed. In the ammeter it is desirable to have the resistance of the instrument a minimum in order that the drop across its terminals may be as small as possible, and the largest possible remaining E.M.F. left available to force the current through the external circuit, whereas, in a voltmeter, the resistance is made as high as can be done in order that the current it draws may be a minimum and not appreciably reduce the potential between the points of attachment. Further, with ammeters of the shunt pattern, the potential available for forcing the current through the instrument windings is only that due to the drop in potential across the terminals of the instrument shunt because of the resistance of that shunt, and that resistance must be kept very low in order that this portion of the instrument may not become too bulky and costly, whereas, in a voltmeter, the majority of commercial potentials that have to be measured are comparatively high, usually well in excess of 1 volt, so that that amount of E.M.F. may be dropped across the windings of the active coil proper. One other feature is that in shunt ammeters, owing to the errors introduced by varying temperature of the instrument windings, conservative current densities must be employed in order to prevent the current flowing through them from causing a sufficient temperature rise to introduce in itself appreciable errors. Such is not the case with voltmeters. Here 1 to 3 volts is the ordinary drop across the active coil terminals, this figure being imposed by the fact that instruments of this low range are sometimes required, and by the additional fact that to obtain a greater one windings would have to be used of a diameter so small as to render their employment almost impossible for mechanical reasons. A large auxiliary resistance must be connected in series with the active coil itself, therefore, in order that it may drop all of the potential except the 1 to 3 volts required by the coil windings, and the temperature coefficient of that resistance may be selected so as to make the apparatus, as a whole, practically independent of temperature influences. Suppose, for instance, that the instrument in question is of 150 volts capacity and that 1½ volts potential at the active coil terminals would cause full scale deflection; the temperature coefficient of the coil circuit would probably be about that of copper, *i.e.*, the resistance would increase about 1 per cent, for a temperature rise of 5°. If the resistance that was placed in series with this active coil, in order to make it necessary to apply 150 volts potential difference to the terminals to give full scale, is of a metal having a zero temperature coefficient, a change of 5° in the temperature of the instrument would mean a change in the resistance of the instrument as a whole, not of 1 per cent, but of .01 per cent.

In other words, for ordinary temperature changes the error is entirely negligible.

With the foregoing differences between a voltmeter and an ammeter understood, a reference to the chapter on ammeters of the permanent magnet type will explain sufficiently the similar direct current voltmeters.

VOLTMETERS FOR BOTH DIRECT AND ALTERNATING CURRENT.

VOLT BALANCES.

The Kelvin-balances that have been described in the chapter on laboratory and commercial standards and mentioned in the chapter on ammeters, can be used for the measurement of potentials also. For this work the centi-ampere balance is chosen, as this demands the least amperage for its operation and is of the highest resistance. The manufacturers supply resistances made of low temperature coefficient metal to be used in connection with the centi-ampere balance to enable its employment in the measurement of commercial voltages. As in these devices the percentage of the total instrument circuit resistance offered by the copper balance coils is high, it is necessary to use in connection with it thermometers that show the coil temperatures and to make proper allowance for any deviation from the normal at which calibration was effected if accurate results are to be had.

REFLECTING ELECTROMETERS.

The reflecting electrometer has been mentioned on page 30. It forms an ideal device for the measurement of potentials in that, as its resistance is infinitely high, no current is drawn from the source under test, and the potential shown is, therefore, that of the source when on open circuit.

It is not, however, common to use such meters for the measurement of low potentials, as they can hardly be said to be of a commercial pattern; the moving element is fiber suspended and hence not portable, and the indications must be read off with a telescope and scale, or a lamp and scale, which does not make the operation any more easy. When a reflecting electrometer is to be used, it should first be tested on direct current by attaching to its terminals a battery of low E.M.F., observing the deflection, reversing battery connections, and observing the fresh deflection and then comparing notes. In the case of the great majority of electrometers it will be found that the two indications do not agree. This is because the suspension supporting the moving vanes is necessarily an electrical conductor and almost invariably of different metal from that forming the vanes, the former being ordinarily of phosphor-bronze strip and the latter of sheet aluminum. When dissimilar metals are in contact a difference of potential exists between them, and, although this is small, it is comparable with that of potentials within the range of measurement of the electrometer. The instrument will, therefore, read higher with the outside polarity presented in one way than when connections to it are reversed, so that if it was originally calibrated on direct current it should always have a given binding-post attached to the direct current terminal of the same polarity as when originally calibrated. When used for measuring an alternating E.M.F. the electrometer will read high or low by an amount equal to the contact E.M.F. between the suspension and the vane. It will read high if the calibration with direct current was effected with the

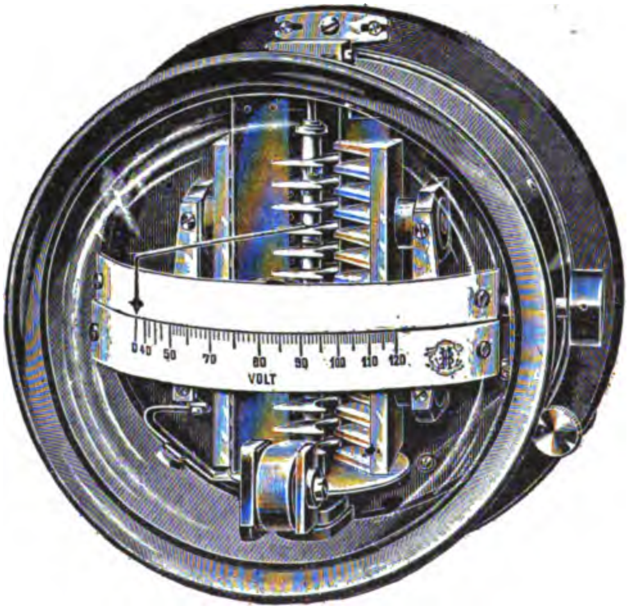

FIG. 149.

outside E.M.F. opposing the contact E.M.F., and low if the two assisted each other. A proper allowance must, of course, be made for this factor.

ELECTROSTATIC VOLTMETERS.

While the sensitive fiber suspended reflecting electrometers are little used except for laboratory purposes, the same principle is employed with considerable success in commercial work where the potentials involved are sufficiently high to give large deflecting forces of a magnitude comparable with those existing in electromagnetic or permanent magnet instruments. Other things being equal, the rotational effort exerted on the moving element varies as the square of the potential, so that as the potentials increase, the point at which sufficient torque is obtainable is rapidly reached. Where the potential regularly used is too low to give the desired directional effort with a single pair of vanes of practicable size, the number of pairs may be multiplied, as in the case of the Kelvin multicellular voltmeters mentioned on page 32.

Fig. 149 shows a similar instrument made by Hartmann & Braun. The principal difference between this and the Kelvin instrument is in the shape of the movable vanes and in the fact that the indications are damped by an aluminum disk swinging between the poles of a permanent magnet instead of a disk immersed in oil.

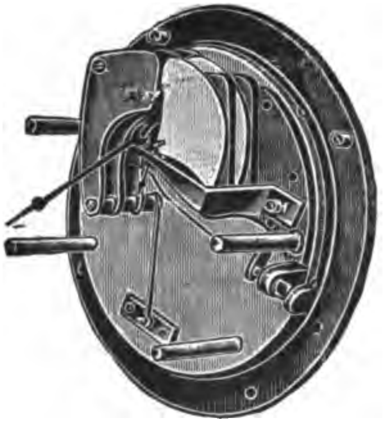

Fig. 150.

Another type of electrostatic voltmeter is shown in Fig. 150, wherein the vane system is not symmetrical to the axis about which it rotates, and the damping is accomplished by means of an air vane fitting closely in a nearly tight box. The sensibility of this pattern of meter cannot be made very great, the minimum full scale voltage for which they can be constructed being 1,000.

As electrostatic voltmeters are as a rule used for high potential work, it becomes necessary to take special precautions to prevent a spark from passing from the fixed to the movable elements. The distance between the two is made a minimum in order that the actuating force may be as large as possible, and fuses of very fine wire are ordinarily placed in the instrument circuit so that if a spark should pass, the current flowing through conducting paths thus opened will blow the fuse and disconnect the apparatus. This expedient is, however, not always efficacious, as the amount of current is but small, and the apparatus may be ruined before it attains a strength sufficient to melt the safety fuse. Additional protection is afforded by enveloping the stationary plates in a coating of mica or hard rubber. A superior plan is to make connection between the instrument and the line, not directly, but through the intervention of condensers whose insulation resistance may be made as high as is desired. With this arrangement it is practically impossible to burn out the voltmeter, if properly designed.

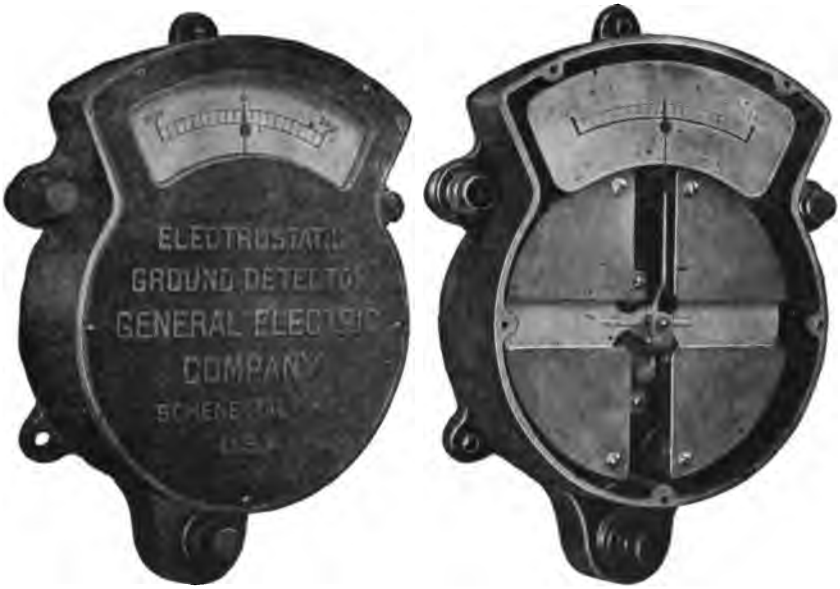

Fig. 151.

Electrostatic voltmeters *per se* are not in common use in this country, but instruments based on the electrostatic principle and used to indicate the occurrence of a ground on high potential lines are very popular. Such devices are called "ground detectors," and one is shown in Fig. 151. In use the movable vane is electrically connected to a ground-wire, and the diametrically opposite fixed quadrants to either side of the line. As long as the circuit is not grounded, the potential difference between each pair of quadrants and the movable element is the same, and the index points to zero. Should, however, one of the lines become wholly or partly grounded, the potential difference between the quadrants attached to that wire and the movable element is less than that between the other wire with its attached pair of quadrants and the same movable element, so that the needle is deflected, the direction of the deflection showing the side of the line that is faulty.

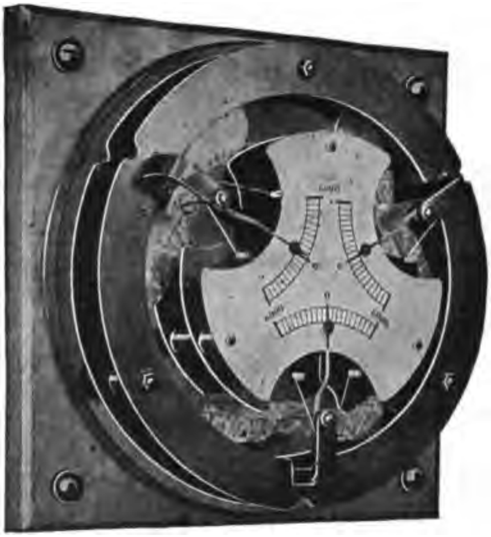

FIG. 152.

Where multiphase circuits are used, three single-phase electrostatic ground detectors like the above are often employed, and these may conveniently be built into a common case as is shown in Fig. 152.

A more recent instrument makes use of three stationary plates (in a three-phase system) placed 120° apart, each connected to one of the line wires. At the center of the spherical triangle formed by these plates there is pivoted so as to be movable toward any of them, a fourth vane electrically connected to ground.

It is evident from Fig. 153 that if any one of the three line wires becomes grounded, the movable vane will move away from the central position where it is normally held by the springs shown, because the original equality of difference of potential between each fixed vane and the moving one is disturbed, and that the deflection of the pivoted vane, therefore, shows not only that a ground has come into existence, but on which of the conductors it is located. A perspective view of a three-phase ground detector of this kind is given in Fig. 154.

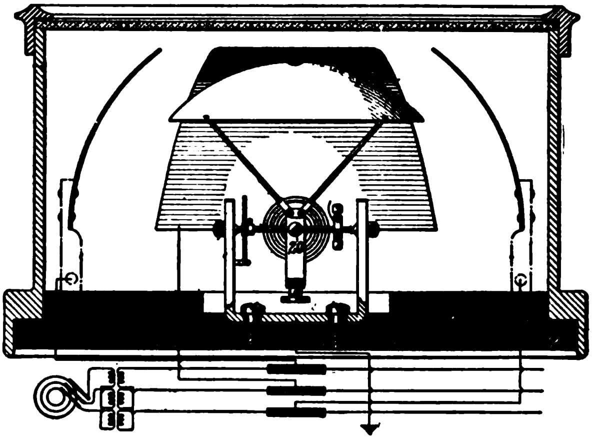

FIG. 153.

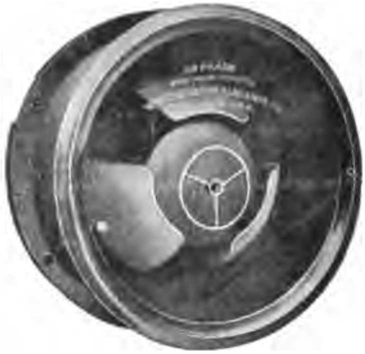

FIG. 154.

An electrostatic ground detector in which the repulsion between sharp points similarly charged is used instead of the attraction between flat plates oppositely charged, is shown in Fig. 155.

In all electrostatic voltmeters, it is advisable to have the protective casing of metal in metallic connection with a well-grounded plate, as the latter then serves not only as a shield against disturbances due to foreign electric charges, but will prevent injury to the attendant if he should accidentally come into contact with the meter.

DYNAMOMETER VOLTMETERS.

As in the case of other types of ammeters described in the preceding chapter, an electrodynamometer may be used to measure voltages by forming its coils of many turns of small diameter wire instead of a few turns of wire of large cross-section. The Siemens dynamometer, as illustrated on page 165, is however seldom used in its original form for potential measurements, as the currents involved are so small that the use of mercury cups is unnecessary. They are usually replaced by two torsion springs, the current being led into and out of the moving coil through these. In some patterns there is but one spring, a very flexible conducting strip being employed to carry the current away.

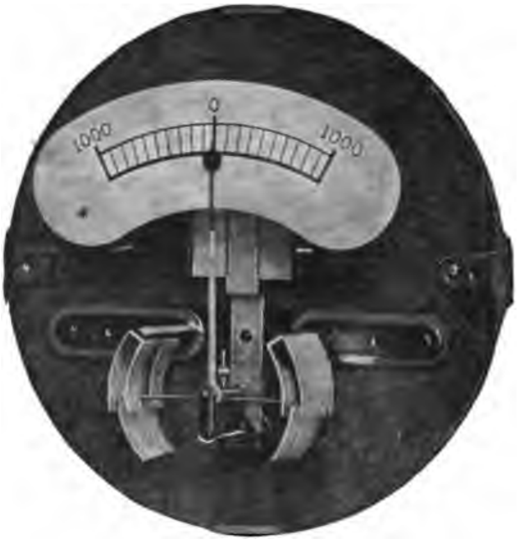

FIG. 155.

A typical form of the modified electrodynamometer class of voltmeter is the Weston instrument, whose moving element is shown in Fig. 156. As will be noted, this consists of a circular coil of many turns of wire, equipped above and below with pivots which rest in appropriate jewel bearings, and having its coil ends in electrical contact with two volute springs secured to the pivots. As the outer extremities of these springs are attached to stationary terminals, they serve as an opposing force to the coil motion. This circular coil is placed within a larger stationary one whose windings are connected in series with it so that the current in both reverses simultaneously, and the resultant effort is to urge the coil to rotate in a given direction.

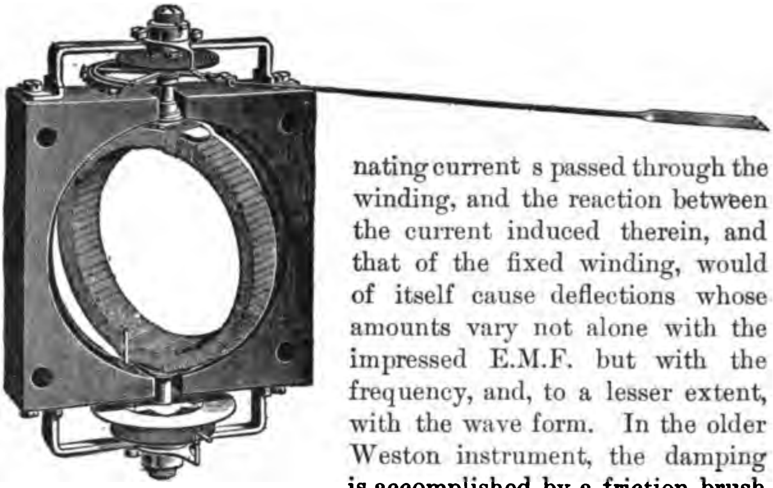

FIG. 156.

Such instruments cannot have their indications damped by winding the movable coil on a metallic framework forming a closed electrical circuit, as in the case of permanent magnet instruments, because, if this were done, the framework would act as a short-circuited secondary of a transformer when alternating current s passed through the winding, and the reaction between the current induced therein, and that of the fixed winding, would of itself cause deflections whose amounts vary not alone with the impressed E.M.F. but with the frequency, and, to a lesser extent, with the wave form. In the older Weston instrument, the damping is accomplished by a friction brush which acts adjustably on the small disk secured to the lower pivot, as shown in Fig. 156. In the later Weston model, and in other similar instruments, the damping is accomplished by means of an air vane moving in a nearly closed box.

While such dynamometer voltmeters may be used for the measurement of E.M.F.'s of either direct or alternating current circuits, they are open to certain objections. In the first place, the magnetic field furnished by the stationary winding for the movable one to work in is necessarily of feeble intensity, as compared with the magnetic field in direct current instruments, this being because the whole of the magnetic circuit is through air, and because the number of energizing turns must be kept down for reasons to be explained later. A weak instrument field means that the apparatus is sensitive to the influence of neighboring foreign fields. This feature is of no importance, when alternating potential is being measured, as then the direction of the current through the movable element is being continuously reversed; an external field that would cause the indications to be high when the current is flowing in one direction exerts an equal influence to make the indication low with the current flowing in the reverse direction, and the average result actually indicated is correct. With direct current, however, this does not hold good, and it is necessary, therefore, to make two readings with a given source of d.c. E.M.F., one so that the current flows through the apparatus one way, and the other with it flowing the other way, and to take the mean of the two to arrive at the correct result. To be sure, a dynamometer instrument of this kind may be orientated until its indications are the same, irrespective of the polarity of the attached conductors, but to find the exact position is a tedious matter, and seldom worth while.

Another objectionable feature of the dynamometer type of voltmeters, and which, in fact, applies to all alternating current voltmeters except those of the electrostatic type, is their low resistance. It is necessary that this should be low, because the number of turns must be kept down in order that the resistance offered to the flow of a continuous current may be practically the same as that offered to an alternating current; that is, that the resistance and impedance shall be nearly alike, and the small number of turns thus allowed must be of coarse low-resistance wire, in order to carry without overheating the amount of current necessary to supply a field of the requisite strength. If the self-induction of the instrument is not made negligible, the less resistance encountered by direct current would allow of a current flow greater than that caused by a source of alternating E.M.F., and the instrument would read higher on direct than on alternating current for the same voltage.

ELECTROMAGNETIC VOLTMETERS.

Here again, as in many preceding instruments, we find that the only difference between the voltmeter and the ammeter is that the former is wound with many turns of fine wire instead of a few of coarse wire. The internal mechanism of an electromagnetic voltmeter of the solenoid type is shown in Fig. 157. Obviously, in the case of the magnetic vane form, the same substitution of fine for coarse wire is of itself sufficient to effect the conversion of the instrument.

Where electromagnetic voltmeters are to be used for general test work, and it is desired that their indications shall remain correct independent of the frequency of the circuit on which measurement is being made, the number of turns in the stationary spool must, as already explained, be made a minimum in order that the self-induction may be as small as possible. In order to reduce this value to a point where the difference between the resistance and impedance is practically zero, the resistance must be made so low that if a good fraction of the maximum potential for which the apparatus is designed is applied to it for any considerable period, the heat generated will change the resistance, and hence the accuracy of the indications, because, as stated in the opening remarks of this chapter, the accuracy of the indications of a voltmeter depends upon the assumption that the *R* of the instrument is constant. For portable instruments of this class, therefore, that must be correct on any frequency and on direct current as well, low-resistance windings are employed, and it is necessary to observe care that the meter be attached to the circuit for only brief periods in order that its heating may not introduce appreciable errors. They are usually provided with spring-actuated contact keys, so that current will not flow through them unless the key is intentionally depressed, and then only as long as it is kept depressed.

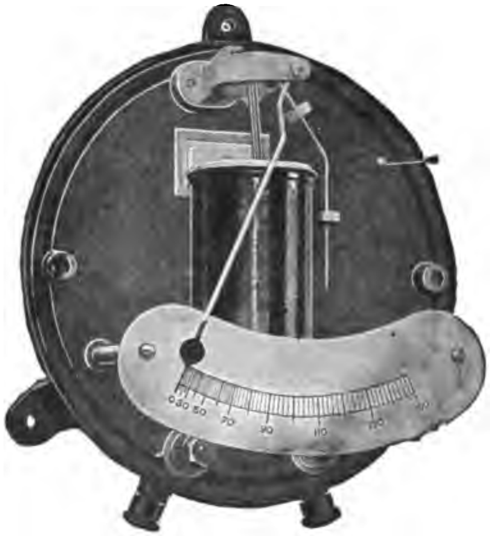

FIG. 157.

Where such instruments are not intended for all-around work, but are of the switchboard pattern, to be used in connection with one installation only, the frequency of the current delivered by that installation is ascertained in advance and the instrument calibrated to be correct for that frequency. Comparatively high self-induction is in this case permissible, which enables the use of enough wire to make the resistance sufficiently high to keep the current flowing down to a value which will not introduce heating errors.

To boil the above down, portable alternating current voltmeters of the dynamometer and electromagnetic types are accurate on varying frequencies only by sacrificing their resistance and by sacrificing the possibility of leaving them continuously in circuit without heating error; switchboard instruments of either type may be left continuously in circuit and are of higher resistance, but are accurate only on the particular frequency for which they are calibrated.

HOT-WIRE VOLTMETERS.

It is not necessary to go into the details of these, for, as in the case of the electromagnetic instruments above, they differ from the hot-wire ammeters only in that the resistance of the wires is made as high as possible in order to consume a minimum amount of current, and in having auxiliary resistances coupled in series with the thermal wires in order to adjust the calibration instead of having shunts coupled across the terminals.

INDUCTION VOLTMETERS.

Here again we have merely high-resistance ammeters calibrated to show potentials. The description of the former instruments covers these fully.

COMPENSATED VOLTMETERS.

Where a voltmeter is used in a central station, the ordinary type gives merely the potential at the station bus-bars and conveys no idea of the voltage at the centers of distribution, the latter varying with the load on the lines. It is important that the potential at the distribution centers be known at the station, as the primary object of the station regulation is to maintain the potential at the lamps as nearly constant as possible, the station voltage being of secondary interest only. It is, of course, possible to run a pair of small wires whose resistance is low as compared with that of the voltmeter, back from the distribution centers to the station and to attach an ordinary voltmeter to them in order to ascertain this factor. Such an expedient is, however, costly, and in consequence various efforts have been made to design potential indicators which will show the distribution center voltage without necessitating these return or "pilot" wires.

One form of these compensated voltmeters is shown in Fig. 158. This is an instrument of the permanent magnet type

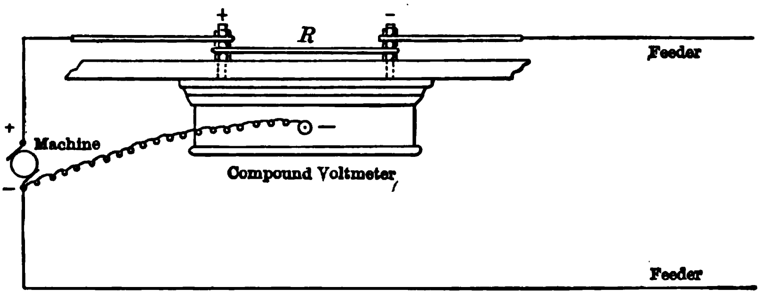

FIG. 158.

suitable for direct currents only, and has its movable coil double wound; one of the windings is a regular voltmeter winding, and if the other is disconnected causes the instrument to read volts in the ordinary way. The other winding is like that of an ammeter and receives its current because of the potential applied by the drop across a shunt connected in the outgoing circuit. The electrical connections are made so that the effort of the latter opposes that of the voltmeter winding. When, therefore, no current is flowing through the line the instrument indicates the station potential. When current is being drawn, the drop across the shunt causes the deflection of the instrument needle to be less than that due to the station potential by an amount dependent on the strength of the current. The adjustment is so made that this diminution is the same as the drop along the supply line to the center of distribution with a given current flow, and the apparatus thus indicates the potential at the distribution center without necessitating the employment of "pilot" wires.

A similar expedient is employed in the case of alternating current apparatus, the plan being as indicated in Fig. 159. Here the voltmeter is connected to the terminals of one of the windings of a voltmeter transformer, the primary coil of the same being connected across the line. The transformer has a third winding of a few turns of heavy conductor, through which the outgoing current must flow, and which is so connected that its tendency is to decrease the secondary E.M.F. induced by the primary winding. In commercial transformers of this type, leads are tapped out from the windings and terminate in contact buttons so that the degree of compensation may be varied to suit the conditions of various installations. A compensating voltmeter transformer of this kind is shown in Fig. 160.

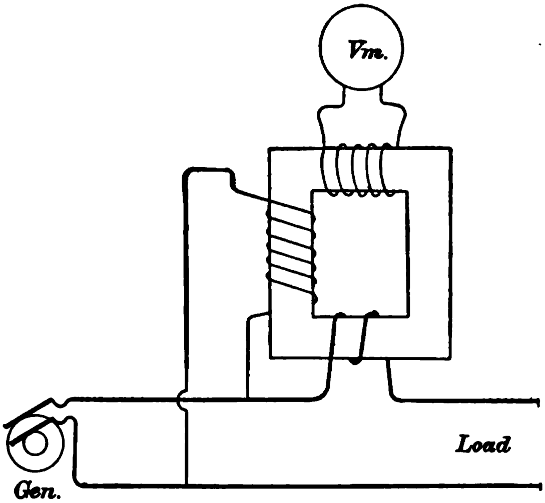

FIG. 159.

SUPPRESSED SCALE VOLTMETERS.

In ordinary central station practice the range of voltage to be covered by the station voltmeter is very small. For instance, in a plant running normally at 110 volts, an instrument whose lowest indication is 100 volts and the highest 120 volts serves all practical purposes. If the same length of scale can be included between these two points as that included between the zero and full scale markings of an ordinary voltmeter covering all values intermediate between zero and 125 volts, the width of each scale division representing a volt is evidently over five times as great, and voltage determinations may be made with that much higher accuracy. The station attendant also may stand much farther away from his instrument and still be able to read the voltage with the same exactitude.

Instruments having such scales are called "suppressed scale voltmeters," or sometimes "potential indicators," and the method of attaining the end is as follows:

FIG. 160.

In the case of direct-current instruments of the movable coil spring opposed type the springs are wound up by turning their abutments until they have a sufficient tension to make it necessary to apply the desired minimum voltage before the needle can start to move across the scale. If no change other than this were made, the value per division representing a volt would be no greater than in the original device. If, however, the resistance in circuit with the moving coil is cut down to say one half the original amount the current flowing through the coil will obviously be doubled, and this would cause it to move twice the distance against the unchanged spring tension as the coil in the original apparatus. If, further, the number of turns forming the moving coil is doubled, the doubled number of times that the current flows through the field coil will cause a doubled deflectional effort. By combining these two expedients it is perfectly possible to attain five or for the matter of that ten times the torque used in a meter having divisions running from zero on upward, and thus to attain the desired end of having the value per division one fifth or one tenth as great. A permanent magnet-moving coil instrument of this suppressed scale pattern is illustrated in Fig. 161.

Where the voltmeter is of the electromagnetic type, and the opposing force is supplied by a weight on which gravitational attraction exerts a stronger and stronger pull as the angle of deflection of the needle increases, the expedient of winding up springs can of course not be used. The plan then employed is to provide a loose weight which rests on a fixed shelf when no current is on the instrument, but which is lifted by the instrument plunger as soon as this starts to rise a very small amount. The weight thus added is large enough to prevent the needle from moving further, until a higher predetermined voltage is attained, whereupon the weight and the plunger rise together as in the ordinary apparatus. The added deflection per volt impressed is obtained by increasing the number of turns in the stationary current carrying spool and decreasing the resistance of that circuit precisely as in the case of the permanent magnet apparatus.

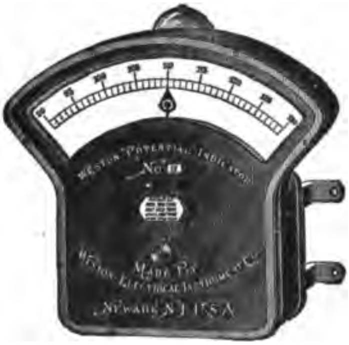

FIG. 161.

CALIBRATION OF VOLTMETERS.

It is of course possible to calibrate a voltmeter by using a known standard resistance and passing through it a known current, the resulting potential difference between the resistance terminals being calculated from Ohm's law. The value of the current strength may be obtained by the voltameter method, if desired, and that of the resistance by any of the absolute methods mentioned in Chapters II and IV. Such a method of establishing potentials is, however, cumbersome, and moreover complicated by the fact that the voltage-reading device is ordinarily of itself of finite resistance and will therefore modify the potential at the terminals of the standard resistance when connected in parallel therewith. The error may be allowed for by simple arithmetical calculation, but of course involves the accurate determination of the resistance of the voltmeter.

A better and much more simple method of voltmeter calibration consists in comparing the indications of the instrument with the E.M.F. of a standard cell by the aid of the already much mentioned potentiometer. If two cells made at different times and preferably one of the Clark and the other of the Weston type are used for the standards, and these are found to agree with one another, it is morally certain that the results obtained are of an accuracy limited only by the accuracy of adjustment of the potentiometer and the closeness with which the instrument indications are observed.

Station Potentiometers.

The ordinary potentiometer capable of measuring every voltage up to its maximum capacity is rather an expensive piece of apparatus and seldom available in commercial installations. By restricting the number of values that the instrument will show to two or three, however, choosing them so that they approximate closely those at which the station instruments are usually run, the apparatus is considerably simplified and much reduced in price. A simple potentiometer for the calibration of station voltmeters made along the lines indicated is illustrated in Fig. 162. The resistance *MN* is provided with terminals at three points only, so that while but three resistance coils only are needed, three potentials can be compared. Three standard cells, *S*, are provided, and there are flexible terminals, *CC*, so arranged that any one or any combination of them may be connected at will. When but one cell is in circuit, the galvanometer inserted in the standard cell line will show no deflection when there is 60 volts difference of potential between *M* and *P*, 120 volts between *M* and *O*, or 240 volts between *M* and *N*. If two cells are used, these values are of course doubled, and if all three, trebled. By these means the apparatus is to a certain extent self-checking as far as the E.M.F. of the standard batteries is concerned, because if with a fixed potential between *M* and *O* no deflection is obtained, with one cell in circuit and when the same potential is applied to the circuit between *M* and *P* and two cells are used there is also no deflection, it is morally certain that both of the standard cells are in proper condition, and that the resistance wire of the potentiometer has suffered no deterioration. A resistance *R* of about 10,000 ohms value is inserted in the cell circuit, so that no detrimental current can flow and momentarily affect the cell accuracy even if the potential applied to the potentiometer resistance terminals differs widely from the normal. A short-circuiting key, *H*, is arranged so that this resistance may be cut out as soon as it is apparent that balance is nearly attained in order to utilize the full sensibility of the outfit.

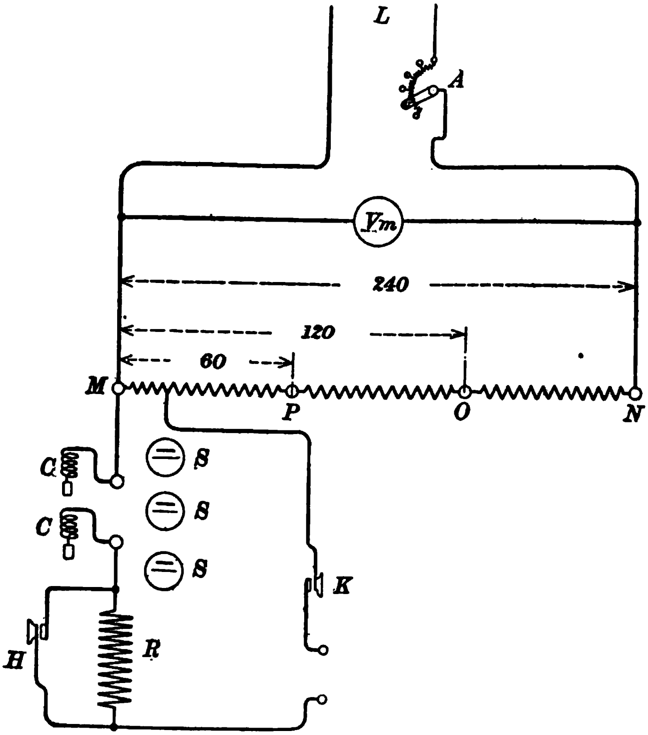

FIG. 162.

In this station potentiometer it is necessary to vary the applied E.M.F. until balance is attained as indicated by the absence of a galvanometer deflection instead of moving the galvanometer contact along the potentiometer wire. The voltmeter that is to be calibrated is therefore connected with its one terminal to the wire *M* and the other to *N*, *O*, or *P*, according to the value de-
]

sired, and the applied E.M.F. varied by a resistance *A* in the supply line until balance is reached. As in the majority of stations the working potential is either nearly 120 or nearly 240 volts, and the fact that the working voltmeter is accurate on these potentials need alone be established, this simple instrument answers practically all station requirements.

The Wheatstone Bridge for Calibrating Voltmeters.

If a standard cell and a galvanometer of moderate sensibility are available, the ordinary Wheatstone bridge may be used to advantage in checking the calibration of voltmeters. The procedure involves as a first step the measurement of the resistance of the voltmeter as closely as possible, using the bridge in the ordinary way for that purpose. The apparatus is then connected up as shown in Fig. 163. To take a concrete case, suppose the voltmeter to be of 150 volts range and that its resistance has been determined as 15,000 ohms. The source of E.M.F. supplies 150 volts, or over, and the standard cell gives 1.019 volts. The error of the voltmeter when 100 volts difference of potential exists at its terminals is desired. Evidently, with 100 volts at the voltmeter terminals, there will flow through its 15,000 ohms of resistance a current of $\frac{100}{15000} = .006667$ amperes. In order that this same current, which necessarily flows through the bridge also, may cause a difference of potential equal to the standard cell voltage at the bridge terminals, plugs must be withdrawn to insert $\frac{1.019}{.00667} = 152.8 +$ ohms at that point. The ordinary bridge has no $\frac{1}{10}$ ohm coils, and the best approximation that can be

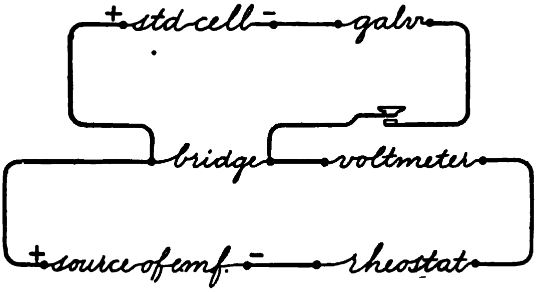

Fig. 163.

made will therefore be 153 ohms. Figuring backward from this point we find that $\frac{1.019}{153} = .00666$ amperes must flow through this to cause the drop to equal the standard cell voltage, and that this current causes a drop of $.00666 \times 15{,}000 = 99.9$ volts across the voltmeter terminals. The voltmeter needle should therefore indicate 99.9 volts when the regulating rheostat in the supply circuit has brought the current strength to a point such that the galvanometer shows no deflection when the key in its circuit is closed, and if it does not, the difference is the error at that point.

Similar checks may be made at any point on the scale.

In practice, the bridge resistance that has been calculated is first plugged in and the rheostat manipulated until the voltmeter indicates approximately the right potential. The key in the standard cell circuit is then momentarily depressed, and if deflection of the galvanometer ensues the rheostat is further varied until this is no longer the case. The voltmeter is then read and the error, if any, noted.

The above method gives a means of checking voltmeters to a degree of accuracy amply high for the most refined station practice, and has the great advantage of requiring, in addition to the instruments that are usually on hand anyway for other work, only an inexpensive standard cell.

Some manufacturers of Wheatstone bridges equip them so that they may be used to measure E.M.F.'s as in an ordinary potentiometer. The plan has, however, nothing to recommend it as against the method just described, and calls for more auxiliary apparatus.

Calibration of Alternating Current Voltmeters.

In the case of alternating current voltmeters it is scarcely possible to go back directly to fundamental standards, as is done with direct current instruments. The calibration is, however, only slightly more difficult in that all that is necessary is to calibrate on direct current by one of the methods described, a voltmeter which will indicate the same on either direct or alternating potentials of like value, such, for instance, as a hot-wire pattern indicating voltmeter or the Kelvin volt balance, and then use it as a standard for comparing the meter under test. If at the expiration of such test the sub-standard is again checked on direct current and found to have its calibration unchanged, the results may safely be accepted as correct.

Of course an electrostatic voltmeter of the Kelvin multicellular or any other convenient type may be used as a transfer instrument in a similar way. If, however, the potentials involved are small, it must be remembered that a correction has then to be applied to compensate for the effect of the potential difference set up by the contact between the dissimilar metals comprising the suspension and the moving vanes respectively, as already described.

CHAPTER VIII.

MEASUREMENT OF POWER.

The power expended in any electrical circuit is measured by the summation of the products of the effective current value and the effective difference of potential at each instant. With direct currents the power is therefore simply the product of the current in amperes and the potential in volts, the watt being the name given to the unit product.

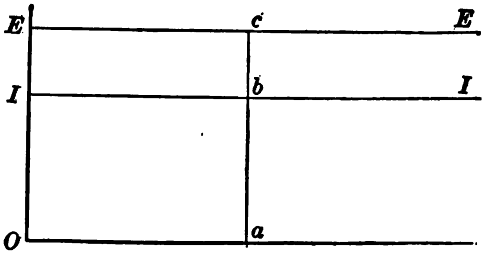

FIG. 164.

When measuring power in an alternating current circuit, however, the simple arithmetical product of effective volts, as shown by the voltmeter, and effective amperes, as shown by the ammeter, no longer gives the true power in watts. This is because nearly every circuit possesses either inductance or capacity, which causes the current to reach a maximum some time later than or in advance of the maximum value of E.M.F. At any instant, therefore, the actual power is the product of the simultaneously existing momentary values of the voltage and current, and the mean of the sum of all of these products is different from the product of the effective voltage by the effective current, as will be evident without entering into a mathematical discussion, by simple reference to Figs. 164, 165, 166, and 167. In Fig. 164 the status of affairs with direct current is shown, the height $a\,b$ of the line I, I above the horizontal axis being drawn to a scale representing the current strength and the height $a\,c$ in a similar manner the value of the potential. The time is laid out along the horizontal axis, so that, the current being continuous and steady, the lines I, I and E, E are, of course, straight and parallel to the axis. It is evident that whatever instant is chosen, the product of $a\,b$ and $a\,c$ remains the same. The case of alternating current is shown in the succeeding figure. Here the horizontal axis $O\,O$ again represents time, the curve, I, I, the values of the current at any instant, and E, E, the potential values at any instant. The reversal of current direction is indicated by drawing the curves below the horizontal axis for such length of time as they are opposite to the initial direction. If the circuit is non-inductive and without capacity, the current varies with and in phase with the potential, and the curves therefore have the relative position shown in Fig. 165. In such circuits the effective watts can be calculated by simply multiplying together the effective volts and effective amperes. If, however, the circuit is inductive, the current no longer varies in phase with the voltage, but its changes in value lag behind it, the relative position of the two being dependent on the relative value of the inductance. Fig. 166 shows the current and potential curves under these circumstances. Here it is evident that the product of the effective volts shown by the voltmeter and the effective amperes shown by the ammeter no longer gives the effective watts. Take, for instance, the point a on the time line. Here the current has the value indicated by the height of the ordinate $a\,c$, but the potential value at that instant is zero, so that their product is zero. The maximum product at any period is no longer the product of the maximum values of the current and voltage but that at some instant, n, where neither is it at its maximum. As

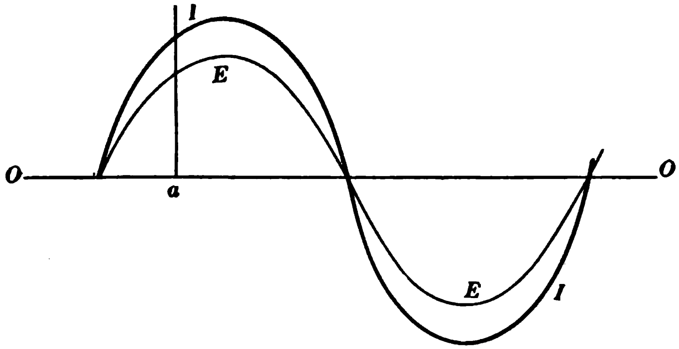

FIG. 165.

algebraic signs must be taken into consideration, we might, theoretically, even arrive at the case given in Fig. 167, where the potential and current curves are in opposing phases throughout, so that their product is zero, although the voltmeter would show the normal effective voltage and the ammeter the normal effective amperage.

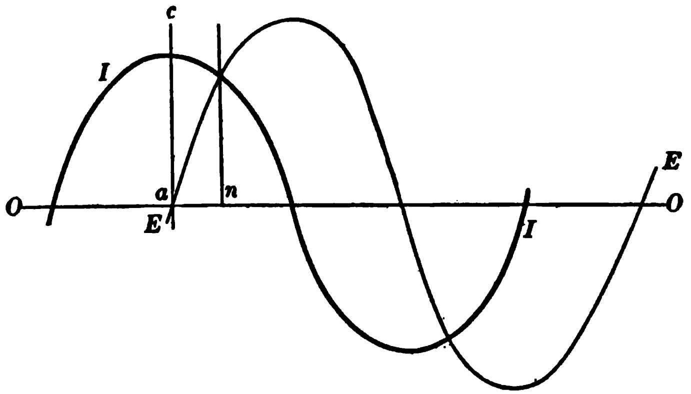

FIG. 166.

The measurement of the displacement between current curves is by no means easy, and even if it were it would be necessary to make calculations to determine energy from volt and ampere readings with alternating current on an inductive circuit. Fortunately there are available means of constructing instruments which will give the watts direct without this necessity.

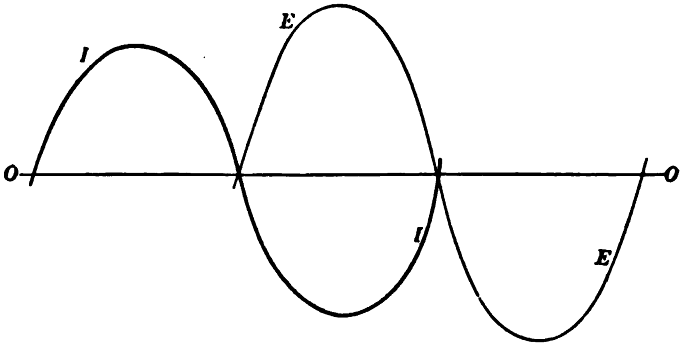

FIG. 167.

DYNAMOMETER WATTMETERS.

The Siemens ammeter described on page 165 may be converted into an instrument that will measure the watts in any circuit by constructing the stationary coil of comparatively few turns of large diameter wire connected so that all of the current to be measured flows through it, and making the movable coil of many turns of fine wire with its terminals connected directly, or through the interposition of a resistance, across the line like a voltmeter. When this is done the field set up by the stationary coil is evidently proportionate to the effective amperage, and that by the fine wire coil to the effective E.M.F. If the current and voltage do not attain their maximum values simultaneously, that is to say, if they are out of phase with one another, the reaction between the two fields will diminish with increasing phase difference, and the instrument indications will be true watts instead of volt amperes.

THE WATT BALANCE.

The Kelvin balance described on page 18 may likewise be utilized as a wattmeter if one of the sets of coils is made to carry the total current flowing and the other is connected across the line, so that the current through it, and hence the magnetic field that it sets up, is proportional to the voltage. As in the case of the dynamometer wattmeter, the fine wire or "potential winding" is used for the movable coils, as the current to be carried to them through the suspending ligaments is then very much less.

WHITNEY WATTMETER.

This is an instrument whose principle is the same as that of the dynamometer wattmeter, but the construction is modified to make the apparatus portable and hence more suitable for commercial measurements. As can be seen from Fig. 168, the heavy current winding is formed of two coils supported on suitable frames, which inclose instead of being inclosed by the fine wire coil. The latter is mounted on a shaft with pointed ends resting in jeweled bearings, and the spring effort which balances the turning effort of the coil, when the button projecting through the top of the instrument case is rotated, is that of a pair of volute springs of flat strip phosphor-bronze, instead of a spirally wound round wire. The current is led into and out of the movable coil through the volute springs, so that the mercury cups used in the Siemens form are done away with. The scale over which the needle attached to the torsion button moves is divided so as to indicate watts directly instead of degrees from which the watts must be calculated by referring to tables or curves. The needle that is attached to the shaft carrying the potential coil, and which is brought back to a reference mark on the dial by turning the torque button to obtain a reading, is allowed a somewhat greater range of movement than the corresponding needle in the Siemens form. A short scale is drawn on both sides of the reference mark, so that the instrument can be used to read wattages differing slightly from those indicated by the needle attached to the torsion head. For instance, if the torsion head needle was pointing to the 50 watt division with a given current flowing, but the other or zero needle was pointing, not to the reference mark, but to the division to the left thereof corre-

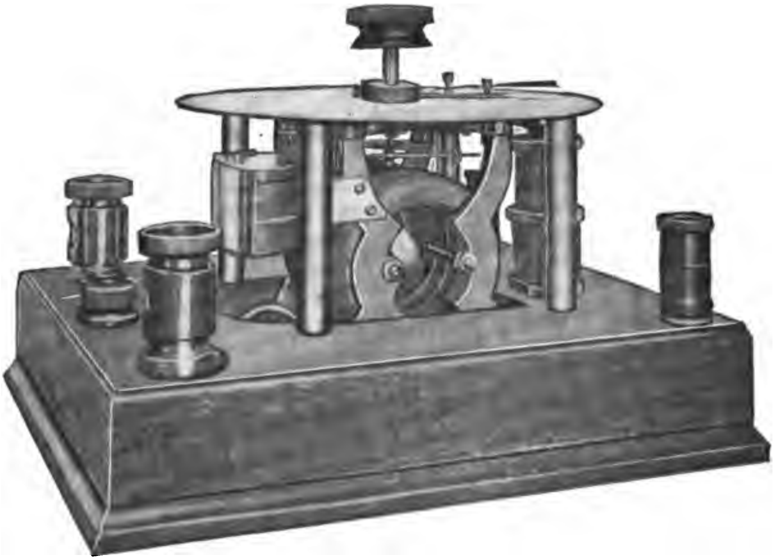

FIG. 168.

sponding to 10 watts value, the true reading is 60 watts, as the divisions of the short scale are so spaced that it would be necessary to turn the torsion head until its attached needle pointed to 60 watts on the principal scale in order to bring the zero needle to its zero line. Similarly if the zero needle pointed to the 10 watt mark at the right of the reference line, the true reading would be 40 watts.

The short scale is convenient in lamp testing, as the torsion needle may be set to the average wattage that the lamps are supposed to take, and the amount in excess of or less than this may be read off at once from the short scale. A better idea of the scale and general appearance of such an instrument may be had from Fig. 169.

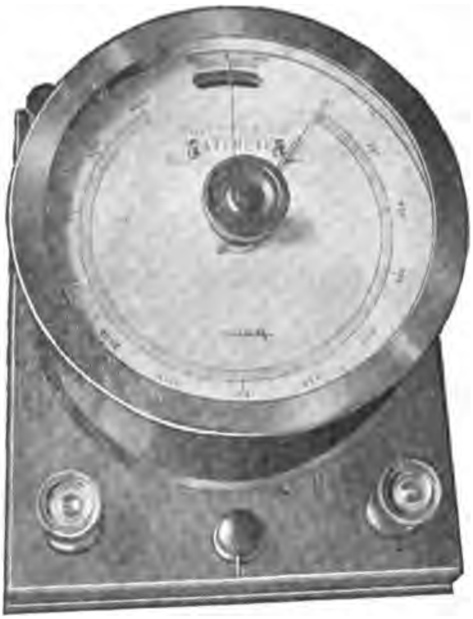

FIG. 169.

WESTON WATTMETERS.

A still further modification of the Siemens wattmeter is the Weston instrument shown in perspective in Fig. 170 and diagrammatically in Fig. 171. Here the heavy wire coil is likewise stationary and surrounds the circular potential coil, the latter being supported on steel pivots resting in jeweled bearings and having the current lead to and from it through volute springs. However, no torsion head is used, and the potential coil, instead of being maintained at practically the same position for every value within the capacity of the apparatus, rotates about its axis over an angle of about eighty degrees. As in the case of the spring controlled voltmeters and ammeters, the opposing force that increases in proportion to the deflection of the needle is supplied by the volute springs, so that, as the reaction between the currents in the two coils is nearly directly proportional to the watts, the scale divisions are nearly equally spaced.

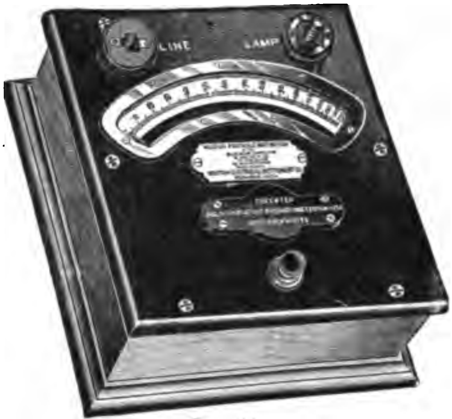

FIG. 170.

This form of instrument has an advantage over the dynamometer types, in that no manipulation is necessary and the needle points at once to the scale mark showing the watts. On the other hand, as the angle between the planes of the current and potential coils is variable, the mutual induction between the two varies with different positions of the needle. For any given difference in phase between the potential and current the apparatus may have its scale divisions drawn so that the indications are correct. If, however, the power factor varies, this varying mutual induction introduces an error that cannot be compensated for, and can be allowed for only when the phase difference is known.

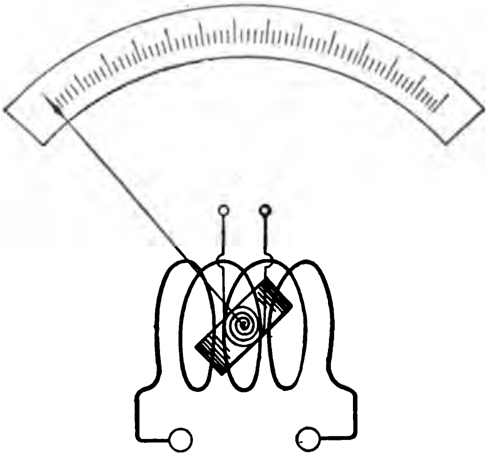

FIG. 171.

The error from this source is minimized by making the mutual inductance of the windings as small as possible, and with proper design can be made negligible for much commercial work where the power factors do not cover too wide a range. However, it is not safe to assume that such an instrument will give correct indications when making measurements on both unity and very low power factors, such as an incandescent lamp load and the energy consumed by the primary winding of an open secondary circuit transformer, for instance, as with the best design there will be a difference in accuracy of at least two or three per cent under such circumstances.

INDUCTION WATTMETERS.

A wattmeter suitable for the measurement of watts on alternating current circuits only, may be made following along the lines of an induction motor. Referring to Fig. 172, if *D* is a disk of good conducting metal, such as aluminum or copper, and *BAB* a series of sheet-iron stampings assembled together and surrounded on the *B* extensions with fine wire windings and on the *A* extension by a coarse wire winding, and these coils are connected in circuit like the fine and coarse coils of a dynamometer wattmeter, the disk will be subjected to a torque proportional to the watts flowing. Briefly, the reason for this is that the alternating current through the coarse winding produces currents in the disk whose paths are as shown by the concentric circles in the figure and of a strength proportional to the current. The current flowing through the fine wire coils sets up a magnetic flux in the legs *B*, *B*, whose strength is proportional to the E.M.F., and the reaction between this and the current in the disk urges the latter to rotate with a torque proportional to the product of the current and the potential, *i.e.*, the watts. The magnetic circuit for the lines of force flowing is made of less

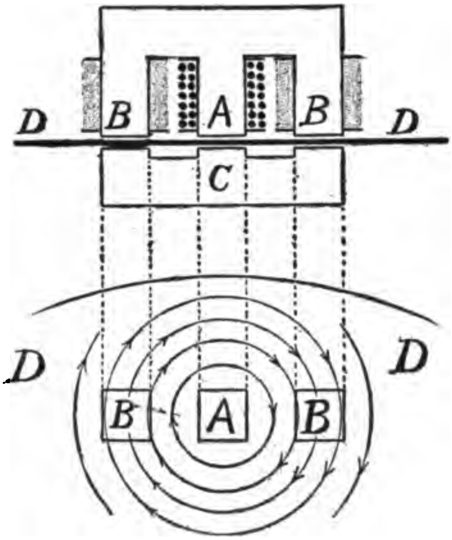

FIG. 172.

reluctance by the addition of the set of stampings *C* placed below the disk.

Having thus an apparatus in which an element is urged to rotate with a torque proportionate to the watts, all that is necessary to convert it into an indicating wattmeter is the attachment of an index to the disk *D*, a calibrated scale over which this needle may swing, and a spring for opposing the disk torque.

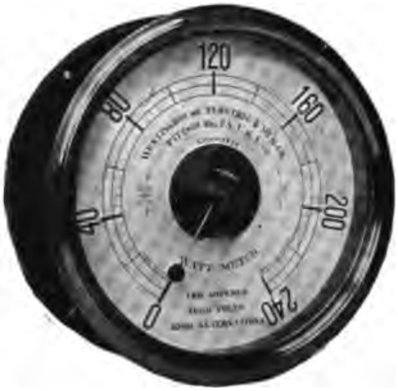

FIG. 173.

The indications of the needle of induction instruments are usually dampened or made "dead beat" by adding a permanent magnet between whose polar extremities the conducting disk rotates, the resultant eddy currents supplying the necessary retardation.

The Westinghouse indicating induction wattmeter is shown in Fig. 173. The conducting disk here takes the form of a cylinder, but the principle being the same as that of the above wattmeter, the operation may be readily understood without going into further details.

HOT WIRE WATTMETER.

A simple and ingenious wattmeter utilizing the expansion of wires heated by the passage of current and proposed by Bauch is diagrammatically illustrated in Fig. 175. Here *a* and *b* are the two hot wires, *S* being a shunt inserted in one current carrying conductor, and *c* a resistance inserted between the junction of the two wires and the other conductor. Starting from the assumption that the elongation of a heated wire is proportionate to the heat that it is called upon to dissipate, it can be shown (see *l'Industrie Electrique*, Sept. 10, 1901) that the difference between the elongation of two wires interconnected as shown in Fig. 175 is proportional to the watts dissipated in the circuit *L*, *L*.

A mechanical arrangement for indicating the difference in the elongation, and hence pull of the two wires, is shown in Fig. 176. Here *c* and *f* are solid levers, *d* and *e* flexible ligaments taking the place of pivots, and *h* an arm with a bifurcated end for actuating the needle as in the hot wire volt and ammeters described on p. 178. When a difference of potential exists between *k* and *l*, but no current flows through the shunt, the wires *a* and *b* are heated alike, as the resistance of the shunt

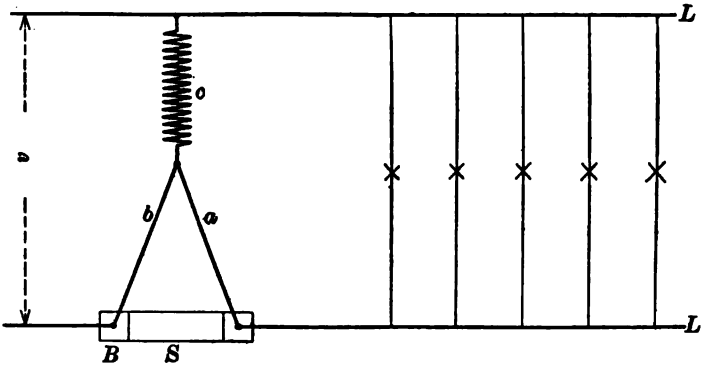

FIG. 175.

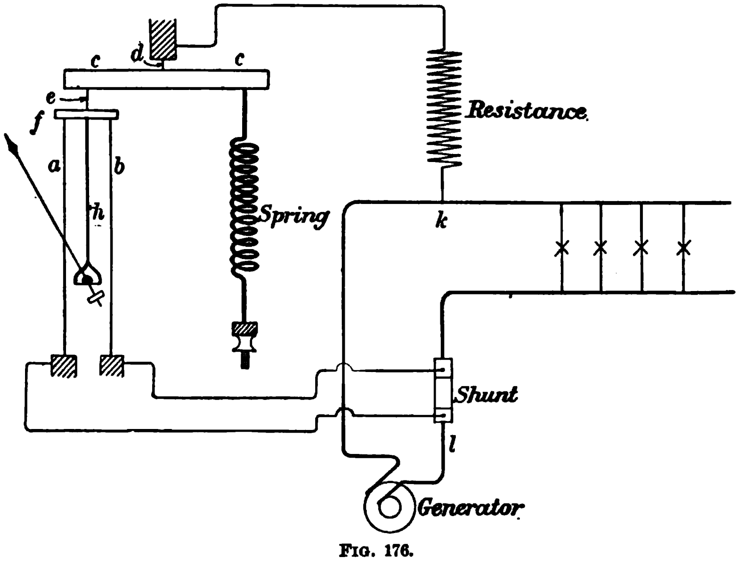

FIG. 176.

is negligible as compared with the rest of the circuit so formed. The lever *h* will therefore move vertically only and fail to rotate the needle. A similar reasoning applies when current flows through the shunt, but there is no difference of potential between *k* and *l*. If there is both a difference of potential and a current flow through the shunt, *b* is heated more than *a*, the lever *f* rocks, and the arm *h* urges the needle up the scale. Its excursions are proportionate to the watts.

CONNECTIONS OF WATTMETERS.

The way in which the current and potential coils of the dynamometer type wattmeters and their equivalents are connected in circuit has a considerable influence on the accuracy of the results obtained. Such connections may be made in either of the two ways indicated by Figs. 177 and 178 respectively. In the former, the potential coil is connected across the terminals of the circuit whose watt consumption is to be measured, the current coil being cut in before it; whereas, in the second case, the potential coil is across the supply line and the current coil inserted further on. With the first arrangement the current flowing through the series winding is evidently that demanded by the load and by the potential coil, and in the second case, while the current is that demanded by the load alone, the potential indicated is not that at the load terminals but that due to the drop across the current-consuming apparatus plus that across the current winding.

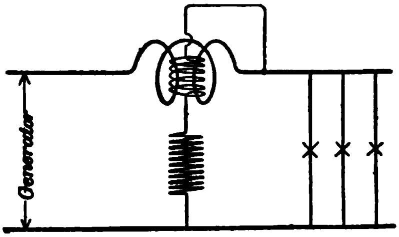

FIG. 177

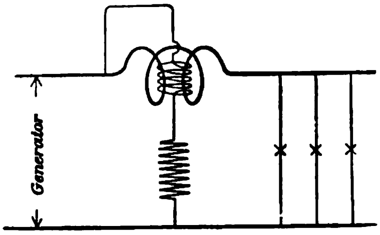

FIG. 178.

To see the effect of these two plans it will be instructive to take an actual example in each case. Considering first the results with connections as in Fig. 177, let the load be a 16 C. P. incandescent lamp, and the potential of the supply mains 120 volts; assume also that the resistance of the potential coil *E* is 4,000 ohms. The current through the lamp may be taken as .5 amperes and that through the potential coil $\frac{120}{4000} = .03$ amperes. The current demanded by the potential winding and which passes through the current coil is therefore six per cent of the current required by the lamp, and the instrument indications are that percentage higher than the wattage expended in the lamp alone. Such an error is, of course, entirely too great even for the roughest commercial work.

If the connections are as in Fig. 178, the results would be as follows: The current flowing through the series coil is now only that demanded by the lamp, but the potential applied to the lamp is less than the 120 volt line potential by the amount of the drop across the series winding. Let the resistance of the latter be taken as .2 ohms, a fair value. With one half ampere flowing, the drop is therefore .1 volts, and as the instrument takes account of the line voltage only, the resultant indications are less than one tenth of a per cent high.

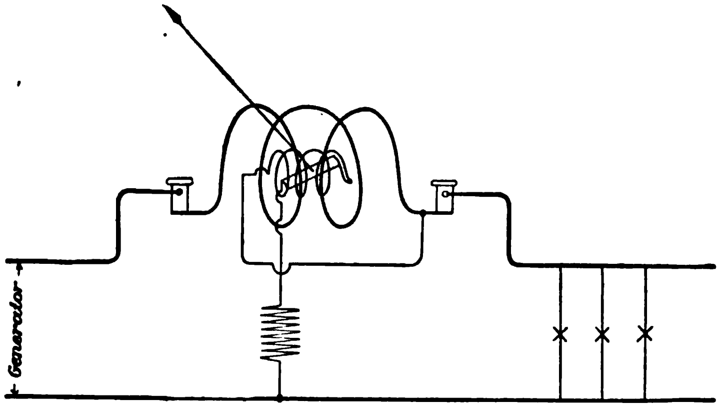

FIG. 179.

This error is less than in the preceding case, but if the current demanded is large and approximating the maximum capacity of the series winding, and the potential applied is low, it also may become appreciable, although seldom as great as in the first case. For accurate work it is therefore necessary that the resistance of both windings of the instrument be known in order that proper corrections may be applied to the results obtained. In almost all cases it is desirable to use the second scheme of connections.

COMPENSATED WATTMETERS.

If certain connections of a wattmeter are made permanently inside of the case, so that it is assured that the circuits will be as in Fig. 177, the error due to the current drawn by the potential coil can be compensated for in a simple manner. Referring to Fig. 179, which shows diagrammatically the internal connections of a wattmeter and the way in which it is attached to the line, it can be seen that in addition to the regular potential coil and the non-inductive resistance placed in series therewith to adjust the calibration, turns of wire convey the potential circuit current around the spool carrying the series coil. The number of these turns is made equal to the number of turns in the movable coil, the result being that the additional fixed coil field due to the additional current flowing through it demanded by the potential winding is exactly neutralized by the back turns of the same current carried around the same number of times through this compensating winding. An instrument so equipped will therefore indicate the watts expended on the receiving circuit without requiring the application of any correction factor.

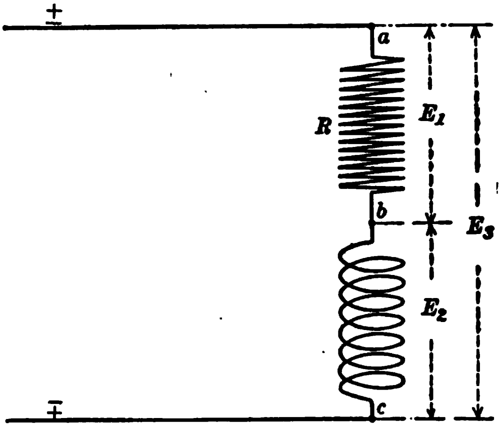

Fig. 180.

THREE-VOLTMETER METHOD.

The watts expended in any given circuit may be determined by using three voltmeters or making three successive measurements with one voltmeter in accordance with the following plan: Referring to Fig. 180, *R* is a non-inductive resistance connected in series with the inductive resistance included between *b* and *c* in which the power to be measured is expended. Three voltmeters are then attached, one to show the potential between *a* and *b*, another that between *b* and *c*, and the third that across the line *ac*. It is not within the scope of this volume to give a demonstration of the correctness of the conclusion, but it is a fact that the watts in *bc* are, under these circumstances, represented by the formula

$$\frac{E_3^2 - E_1^2 - E_2^2}{2R}.$$

To obtain maximum accuracy, *R* should be chosen so that the potential across it is as nearly as possible equal to the difference in potential between the terminals of *bc*. As *R* is in series with *bc*, and the drop across it should be practically the same, it is evident that this method of testing calls for the presence of a testing voltage double that demanded for the normal operation of the device inserted between *b* and *c*.

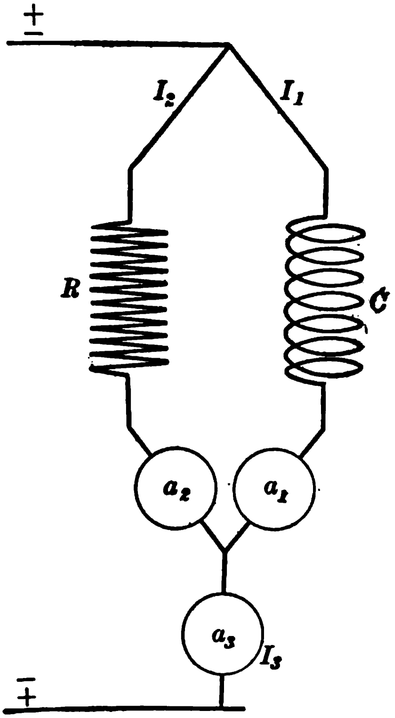

FIG. 181.

THREE-AMMETER METHOD.

Three ammeters may be used to measure the watts expended in any given circuit in a similar way. In this case the connections are made as in Fig. 181, *C* being, as before, the circuit whose consumption is to be determined. Connected in parallel to *C* is a non-inductive resistance *R*, and three ammeters indicating the currents through *R*, *C* and *R* + *C* are inserted as shown. Under these conditions the watt expenditure in *C* is given by the formula

$$\frac{R}{2}\,(I_3^2 - I_1^2 - I_2^2).$$

In contradistinction to the three-voltmeter method, the three-ammeter one does not call for an increased potential for testing purposes, but it does demand increased current. On the other hand, while with the three-voltmeter method it is possible to arrange a switch by means of which connections may be rapidly shifted so that one voltmeter may be used for reading all three potentials, a similar plan is not practicable with the ammeters, owing to the heavy currents involved and the necessity of keeping the circuits intact and their resistances unchanged, so that three meters are essential.

Both the three-voltmeter and the three-ammeter methods have the very serious drawback that a very small percentage error in the accuracy of the indications or the observations of the indications of any of the instruments introduces a very large error in the results. Neither is used in modern practice unless it becomes absolutely necessary to make a test when voltmeters or ammeters alone are available, and every precaution is then exercised to have the readings as exact as possible.

POWER CONSUMPTION OF MULTIPHASE CIRCUITS.

The various instruments for and methods of watt measurement above described are all suitable only for use on simple direct or alternating current circuits involving two conductors only. Where the case involves multiphase currents the conditions become essentially different.

If the line on which measurement is to be made is a four-wire two-phase one, watts are measured just as one would measure them in two independent alternating current circuits, a separate wattmeter being used in the conventional way with each, and their indications arithmetically added. With three-phase three-wire systems two wattmeters must likewise be employed if the results are to be accurate, whether the loads on the different phases are like or unlike. These instruments are to be connected in the circuits, as in Fig. 182, the current coil of one being inserted in one line, the same coil of the other in another line, and the potential coils of each bridged across between their respective lines and the third conductor. The sketch shows the connections of the receiving apparatus as being in delta, but the connections of the wattmeter are made the same if they are arranged in *Y*. The total watts absorbed is given by the algebraic sum of the indications of the two wattmeters. When the power factor of the load is over 50 per cent the algebraic sum is the arithmetical one, but when less than 50 per cent it is the arithmetical difference, so that the indications of the lower reading wattmeter must be subtracted from the higher reading one to get the correct result.

It is essential that the potential coil connections be made as in Fig. 182, as otherwise the results obtained may be erroneous. This caution is necessary because approximately the same potential difference exists between *a* and *b* as between *a* and *c*, and the potential terminals of the wattmeters of the *b* and *a* phases are therefore sometimes connected by careless manipulators to the *a* and *b* ones respectively, instead of to *c*. The magnitude of the error thus introduced can be understood from the following example: Referring to Fig. 183, assume that the power factor of the delta-connected load shown is unity, but that the load is unbalanced, the current in the three phases being 10, 20, and 30 amperes respectively, as indicated. Being of unity power factor, the total current consumption with 100 volts difference of potential between each of the three conductors is evidently 1,000 + 2,000 + 3,000 $\doteq$ 6,000 watts. A wattmeter inserted

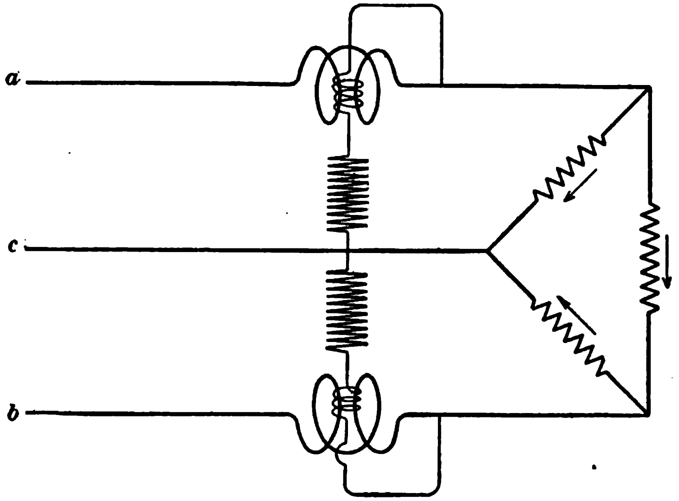

FIG. 182.

at *a*, and having its potential coil connected from *a* to *b*, would indicate 2,500 watts, and one inserted at *c* with its potential coil between *c* and *b*, 3,500 watts, the sum of these being 6,000, as above. If it were attempted to obtain the results by using the wattmeter *a* alone, and transferring its free terminal first to *b* and then to *c*, the sum of the readings would be 2,500 + 2,000 = 4,500 only. The demonstration of these facts is simple, and can be found on page 947, of Volume XL, of the *Electrical World and Engineer*, in an article by McAllister, from which the above example has been taken.

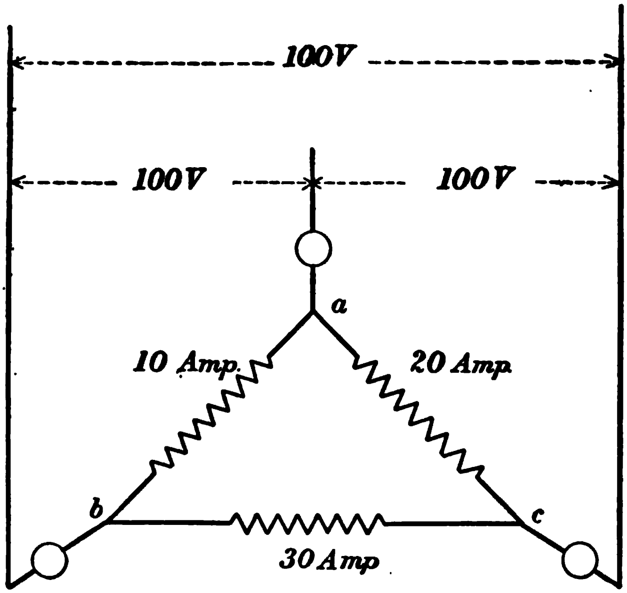

FIG. 183.

CALIBRATION OF WATTMETERS.

The calibration of a wattmeter for direct currents involves nothing more than using an ammeter in series with the current coil and a voltmeter connected to the same points as the potential coil of the wattmeter. The product of volts and amperes as thus indicated is the true wattage. In this measurement it is necessary to reverse the direction of the current through the wattmeter, as in such instruments the magnetic fields are much less powerful than in the majority of direct current meters, and stray fields may introduce appreciable errors which are, of course, eliminated by making two readings with the reversed current and accepting their mean as the true instrument indication.

Calibration on alternating current is a far more difficult matter if sure results are to be had. A dynamometer ammeter, an ampere balance, or a hot wire ammeter may be used for measuring the current, and the corresponding instruments wound with fine wire or an electrostatic voltmeter, for measuring the potential. The product of the volts and amperes in this case will, however, give the watts only if the load being measured is non-inductive. For commercial accuracy a bank of incandescent lamps is sufficiently near to being absolutely non-inductive, although resistance wires doubled back on themselves are better. If the load is not non-inductive it becomes necessary to measure the difference in phase between the current and the potential curves, using one of the methods described in Chapter X, and then to calculate the watts from the cosine of the angle of phase difference and the indication of the alternating current voltmeter and ammeter.

Another way is to use as a secondary standard a wattmeter that has been calibrated on direct current and of which it is known from the design and construction that no errors are introduced with inductive loads. The Kelvin balance and the dynamometer wattmeter as usually made, answer this requirement for all practical purposes at reasonably high power factors, and it is safe to assume that if they show up correct on a direct current test with reversed connections, they will be correct on alternating current also. The only fault that may enter to upset this conclusion is the development of a partial short circuit in one of the instrument windings, but with apparatus that has been tested for a reasonable period, such fault would have its presence clearly indicated by a change in calibration, even if it were not sufficiently serious to make its presence evident by the heating of the short-circuited convolutions when alternating current was passed.

In the few existing wattmeters designed for indicating directly the input into a multiphase system of conductors, the test is made by checking each of the pairs of potential and current windings separately, such apparatus being nothing but two wattmeters with the movable coils mechanically joined, so that the needle indicates directly the sum of the efforts, instead of having two needles whose readings must be added arithmetically.

CHAPTER IX.

MEASUREMENT OF CAPACITY

ABSOLUTE METHODS.

Air Condensers.

In Chapter II, page 33, there was described a standard air condenser devised by Lord Kelvin. The capacity of such a piece of apparatus can be figured directly from its geometrical dimensions, and the known specific inductive capacity of air. The errors that may creep into the geometric measurements are, however, appreciable, and the apparatus itself is bulky and seldom available, so that it is more common to obtain the true value of the capacity of any condenser from absolute units (in contradistinction to comparison methods) by the plan following:

Absolute Capacity Measurement with Galvanometer.

The throw of the coil of a ballistic galvanometer gives the capacity of the apparatus from which the charge causing the throw was delivered if certain characteristics of the galvanometer are known.

In the first place, the galvanometer constant must be determined. To do this, a low potential source of current, preferably a storage battery, is used, across whose terminals is connected a resistance of about 1,000 ohms value. In shunt to a fraction of this resistance, say 2 ohms, there is connected the galvanometer, and the resultant deflection observed after the instrument has settled down. If E is the E.M.F. of the battery, R the resistance of the galvanometer, d_1 the observed deflection, and E_1 the potential at the galvanometer terminals (in this case $E_1 = .002$), the constant is $\frac{R \times d_1}{E_1}$.

The period of vibration of the movable element of the galvanometer must next be determined. This is done by setting it swinging in any suitable way, such as by passing a current momentarily, and then observing carefully the time required for it to make, say, ten to twenty swings. By swings are meant double oscillations from zero to a maximum in one direction back through zero to a maximum in the opposite direction, and to zero again. The number of swings divided by the time in seconds gives the time of vibration T.

The third determination is that of the decrement due to the damping of the motion caused by the molecular friction of the suspending fiber, and of the air currents that the coil must set in motion. The decrement is the ratio of the amplitude of any vibration to the amplitude of the vibration next succeeding. To obtain this the moving element of the galvanometer is set in vibration, and the amplitude of, say, the first and tenth vibrations observed. If the first excursion of the galvanometer index was, say, forty divisions, and the tenth, one division, the decrement would evidently be 1.04. Call the Napierian logarithm of decrement, λ.

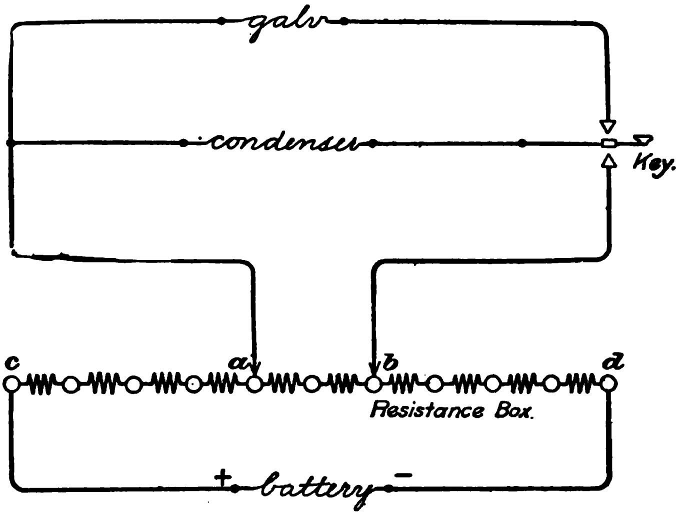

FIG. 184.

With these characteristics determined, the condenser to be measured, the galvanometer, battery, and a resistance box are connected up as shown in Fig. 184. On depressing the key shown in the figure, the condenser becomes charged by the known fraction of the battery E.M.F. determined by the ratio of the resistance included between the condenser terminals, *ab* and the box resistance *cd*. When the key is raised the condenser discharges through the galvanometer, causing it to make a deflection d_2.

The quantity of electricity discharged by the condenser is then calculable from the equation

$$Q = \frac{E_1}{Rd_1} \times d_2 \times \frac{T}{2\pi} \times \left(1 + \frac{\lambda}{2}\right).$$

If the condenser capacity is F and the potential of the source that charged it, E_2, we have, as $Q = FE_2$, $F = Q \div E_2$. Substituting in the above formula, we have

$$F = \frac{d_2 T \left(1 + \frac{\lambda}{2}\right) E_1}{Rd_1\ 2\pi E_2}.$$

In this, as in all capacity measurements involving the use of a ballistic galvanometer, care must be taken to see that the period of a complete swing of the instrument is sufficiently long, as the hypothesis on which the equation rests is that the inertia of the moving system is great enough to allow of the complete discharge of the condenser through the galvanometer winding before the deflection has had time to attain sensible magnitude.

COMPARISON METHODS.

Once having a standard of capacity as determined by the above methods, there are several plans of measuring unknown capacities in terms thereof. Before turning to them, mention may be made of convenient forms of the standard.

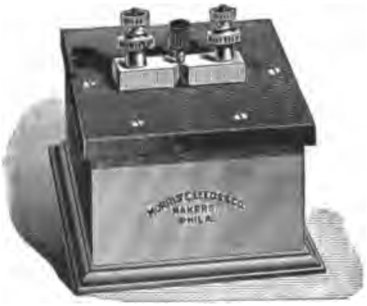

Fig. 185.

In Chapter II the use of air as the dielectric in standard condensers was instanced by the Kelvin instrument, and the use of mica also described. Paper, while inferior to mica for condenser construction, is sometimes employed in rough work, but then must be not only dipped in very hot melted paraffine before being built up, but the condenser as a whole should, after completion, be entirely immersed in the same compound, and allowed to cool with the cake surrounding it in order to exclude the air.

While for very closely adjusted standards a single condenser provided with a short-circuiting plug, as shown in Fig. 185, is commonly employed for measurements of commercial accuracy, it is desirable that the standard capacity be subdivided into units which can be grouped together as desired.

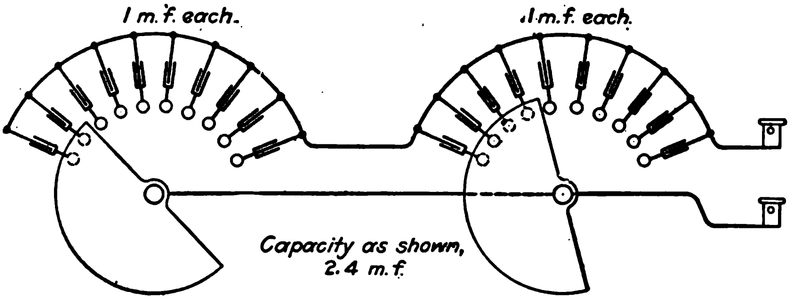

FIG. 186.

This may be done by mounting a number of individual condensers in a common case, and leading the conductors attached to their terminals to a series of contact buttons over which a movable plate may be swept. From Fig. 186 it may be seen that by moving these plates so as to rest on one or more buttons, the one or more attached condensers are coupled in parallel,

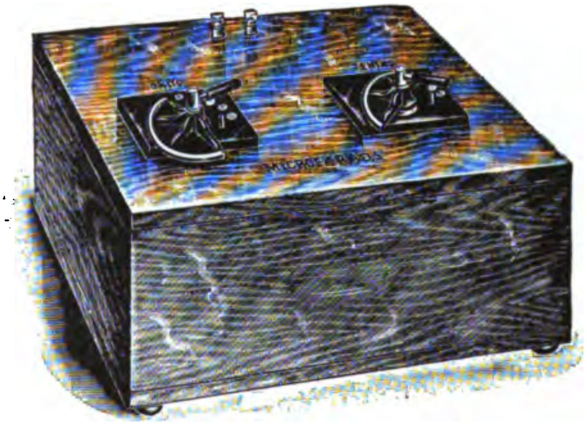

FIG. 187.

and, in the particular apparatus illustrated, a range of from .1 to 10 microfarads in .1 microfarad steps becomes obtainable. A perspective of this adjustable condenser is given in Fig. 187.

An older but still common form of standard condenser has the various individual condensers of which it is built assembled in one case and connected together by movable tapered plugs like those in resistance boxes. Fig. 188 gives the diagram of the connections of one of these, Fig. 189 being an illustration of the complete apparatus. When condensers of the individual capacities indicated by these figures are used, it is evidently possible by inserting plugs so as to couple the various combinations together in parallel, to obtain any capacity between .05 and 1 microfarad in steps of .05 microfarad. Care must be taken that plugs are not placed in the receptacles of opposite ends of a single bar, *A*, *B*, *C*, etc., as if so the condenser is short circuited, and any battery used to charge it would be short circuited also.

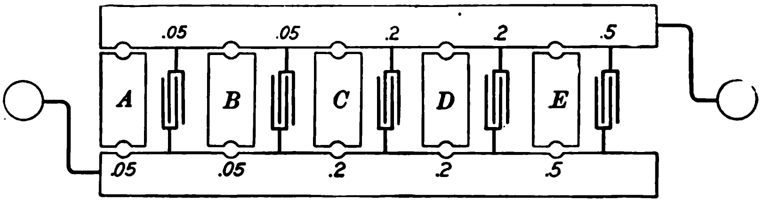

FIG. 188.

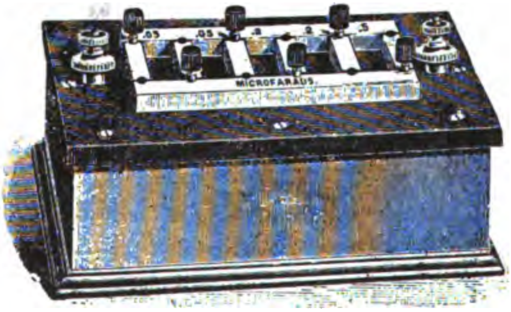

FIG. 189.

This kind of a condenser has the advantage that it is possible to self-check it to a certain extent, as the .05 microfarads may be compared with one another, and the .5 with the other four connected in parallel.

Capacity by Direct Deflection.

As the deflections of a ballistic galvanometer are proportional to the quantity of electricity passed through it, the capacity of an unknown condenser may readily be determined when one of a known capacity is also available by first charging the known condenser from a certain source of E.M.F. and then discharging it through the galvanometer, noting the ensuing deflection, after which the operation is repeated with the unknown condenser in place of the standard one. The galvanometer deflections are then in the ratio of the capacities. The times during which the potential is applied to both condensers must be the same, say five seconds, and it is necessary to take the mean of several readings to allow for small variations in this period. It is also necessary, for the best accuracy, that the standard be selected so that its capacity is as nearly as possible that of the unknown condenser; the whole method is at best, however, a rough one.

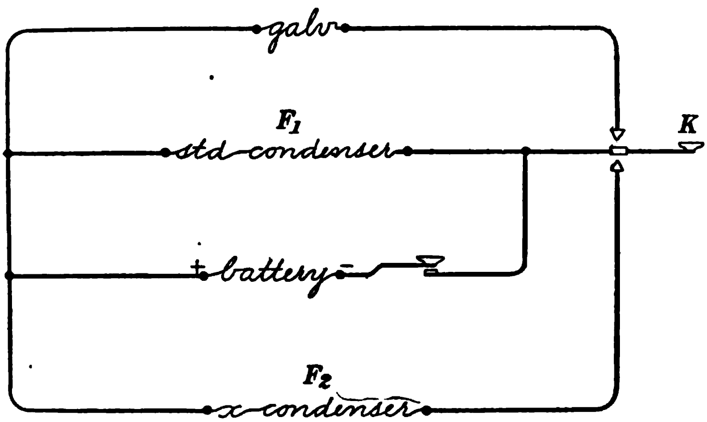

FIG. 190.

Divided Charge Method.

For this, connections are made between a ballistic galvanometer G, a standard condenser F_1, the unknown condenser F_2, a double contact key K, and a charging battery with its key, all as shown in Fig. 190. With the apparatus so arranged, the battery key is depressed so that the standard condenser F_1

is charged, and the key kept closed for an observed number of seconds, say five. The battery key is then opened and key K raised so that the standard condenser discharges through the galvanometer, the throw thus caused being noted. Key K is then again opened and the battery key closed as before to charge the standard condenser. At the lapse of the same period as at first, the key K is depressed, which places the two condensers in parallel, so that the charge in the standard is divided between them in the ratio of the capacities. This being accomplished, the K key is again raised and the deflection caused by the discharge of the quantity of current remaining in the standard condenser noted. If, then, the capacity of the standard condenser be designated by F_1 and that of the unknown by F_2, we have F_1 is to F_2 as D_2 (the second deflection) is to D_1-D_2, in which D_1 is the first deflection. For maximum accuracy, the capacity of the standard should be made as nearly as possible equal to that of the condenser of unknown value.

Bridge Methods.

Condenser capacities may be compared when they are interconnected by a network of conductors arranged like those in the Wheatstone bridge. This method has the same advantage that exists in the measurement of resistances with a bridge; that is, it is a zero one, and errors due to reading the galvanometer deflections are thus avoided. It is further possible to eliminate practically all errors due to inductance.

In the simple bridge method, the standard condenser F_1 and the unknown one F_2 are connected as shown in Fig. 191; adjustable resistances R_1 and R_2, a galvanometer, a battery and a special contact key, *a*, *b*, being also employed. When the *a* end of the key is depressed the condensers are evidently being charged by the battery, and when the *b* end is depressed they are being discharged .through the resistances and the galvanometer. To make the test, *a* is first depressed for a brief interval and then raised for its full height, so that the condenser discharges as stated. If this results in a deflection of the galvanometer, the ratio of R_1 to R_2 is altered and the trial again made, *b* being kept depressed until then, in order that the condensers may be kept discharged. When a ratio of R_1 to R_2

is finally attained such that no galvanometer deflection ensues when *a* is raised and *b* depressed, the relation $\frac{R_1}{R_2} = \frac{F_2}{F_1}$ holds good. This is so because if the galvanometer does not deflect when the condensers discharge, the potentials at its points of attachment to the network are equal; being charged by the some potential, the quantities of current stored by the condensers are proportional to their capacities, and these quantities are in inverse proportion to the resistances R_1 and R_2 in the circuits leading to them.

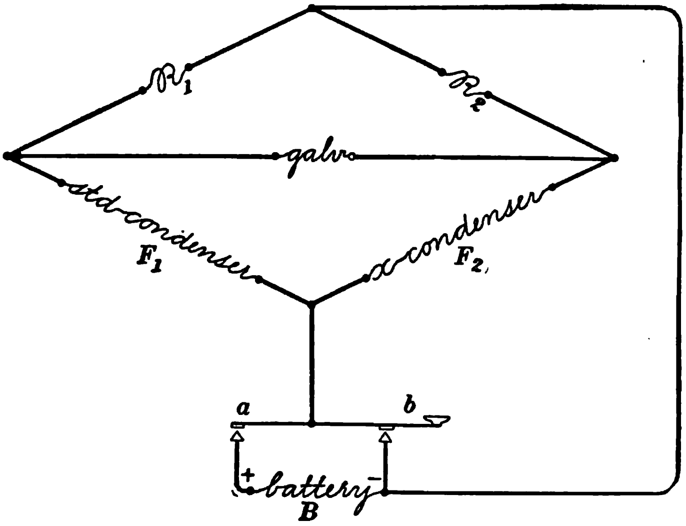

FIG. 191.

In this, as in all other capacity measurements involving the employment of adjustable resistances, it is essential that the latter be absolutely without capacity and without inductance. Such coils are purchasable on the open market, and are best made as follows: Each resistance unit is made up of two wires connected in parallel, each having twice the resistance of that desired for the coil, and each of the two coils is wound into a flat and very thin spiral. The two spirals are placed, their flat faces touching and connected so that the currents flowing through them run in opposite directions. Being now connected in parallel, the opposing windings make the coil non-inductive as the current flows in reversed directions in parallel conductors for a like distance. The capacity of such a unit is negligible, as it forms a condenser in which the potential between its two surfaces is but half of that between the innermost and the outside convolutions, and the distance between the surfaces is that between the wires forming these convolutions. Such construction is necessarily expensive, but must be employed if reliable results are to be had.

Modified Bridge Method.

If the connections in Fig. 191 are modified to those in Fig. 192, the galvanometer and battery positions being interchanged,

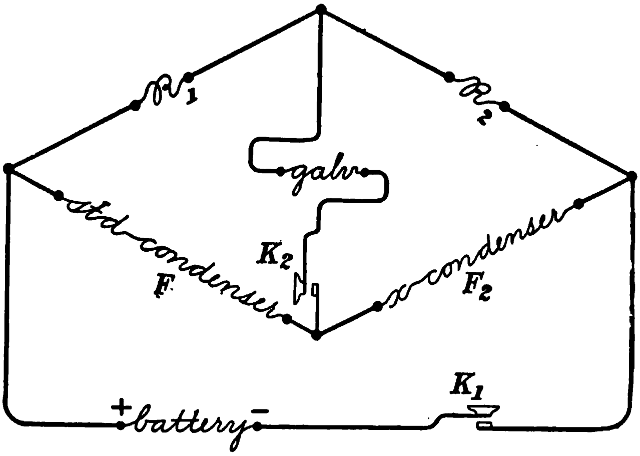

FIG. 192.

we have another method of measuring an unknown capacity in terms of a standard. The keys in the battery and galvanometer circuits are manipulated so that the condensers are charged by the battery and subsequently discharged through the resistances and the galvanometer in a way analogous to that in the preceding method. The values of the resistances are likewise to be varied until no galvanometer deflection results when the condensers are unloaded by depressing the galvanometer key, whereupon the capacity F_1 is to F_2 as R_2 is to R_1. This follows because the condensers, connected in series, must each contain a like quantity, and the discharge from F_1 through R_1 times the potential difference between the terminals of R_1 must equal the discharge through R_2 times the potential difference across R_2. We therefore have the relation

$$\frac{F_1}{F_2} = \frac{R_2}{R_1} = \frac{V_2}{V_1}.$$

Thompson Method of Mixtures.

This method, so called because it involves mixing the opposed charges of two condensers so as to determine whether or not they are equal, is an acknowledged standard, particularly for the measurement of cable capacities, and is also a favorite when the capacity of one condenser is to be accurately determined in terms of that of another.

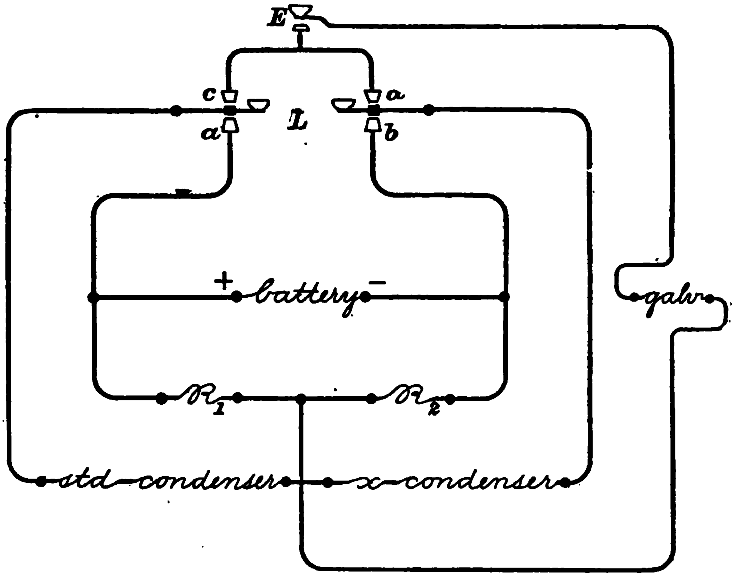

FIG. 193.

In making it, connections are arranged as in Fig. 193. In making a test, the two center buttons of the special key L are first depressed so that the condensers are charged by means of the battery with the potential differences that exist between the terminals of the resistances R_1 and R_2. After this has been done the keys are released, making contact with c and d respectively, which places the two condensers in parallel and allows the charges to mix. If these charges were equal and opposite when the key E is depressed, there will be no galvanometer deflection, as there is no current to cause it. If there should be a deflection, the charges were not alike, and the resistances R_1 and R_2 must therefore be varied until this condition is attained. When it is, the ratio F_1 is to F_2 as R_2 is to R_1 evidently holds. When the capacity of a cable is being measured, the point of junction of the resistances R_1 and R_2 must be connected to earth, as the earth forms the one coating of each condenser.

If the results obtained are to be comparable with others, some standard time of charging must be used, which time may conveniently be chosen as five seconds. The value of the capacities should also be as nearly alike as possible. The key L is a special device known as the Lambert capacity key, one of which is shown in Fig. 194.

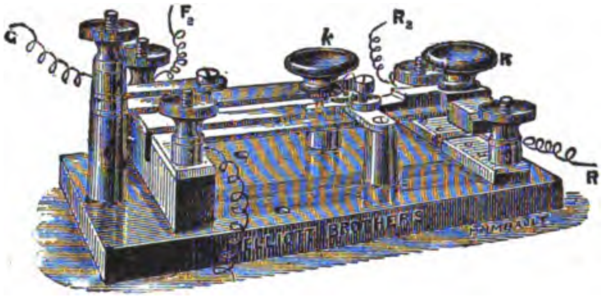

Fig. 194.

CAPACITY BY LOSS OF CHARGE.

If the terminals of a charged condenser are left connected together through a known resistance, R, for a period of T seconds, its capacity can be calculated from the formula

$$F = \frac{T}{2.303\ R\ (\log D_1 - \log D_2)}$$

in which D_1 is the deflection of a ballistic galvanometer caused by the discharge through it of the condenser after it has first been electrified and before the resistance is attached, and D_2 the same after it has been freshly electrified and then left discharging through the resistance R for T seconds. If R, the resistance, is in megohms, the capacity, F, is in microfarads.

If the condenser under test is of the type in which paper is used as the dielectric, its own internal resistance is frequently sufficiently low to enable the above test to be made, it being, of course, in that event necessary to determine the condenser resistance by one of the methods described in that section of Chapter V treating of high-resistance measurements. If the condenser is of the mica-insulated type, its resistance is ordinarily too high to allow of this, and an external resistance of 20 or 30 megohms must be connected across its terminals.

A modification of this test is made by connecting up the condenser, battery, galvanometer, resistance coil, and key, as shown in Fig. 195. With the apparatus so arranged the key is depressed and the steady deflection of the galvanometer noted. The key is then raised and the deflection given read after the expiration of T seconds. If the initial deflection is designated by D_1 and the subsequent one by D_2 the capacity may be calculated by the same formula given above.

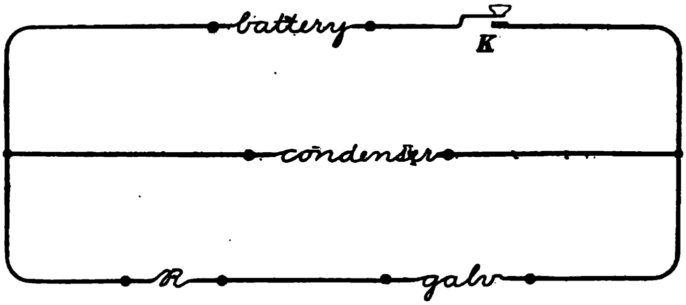

FIG. 195.

In both the foregoing, if the condenser resistance is intermediate between the low value which allows of its use as the resistance through which the charge is dissipated and the high value which makes its figure so high as compared to the one connected to its terminals that the current flow through it is negligible, the value of R in the formula must be calculated from the law of divided circuits, page 94, the true resistance being that of the external one and that of the condenser connected in parallel.

CONDENSER ABSORPTION.

The majority of types of condensers have, to a greater or less degree, a property of their dielectric by virtue of which they will receive a quantity of electricity in excess of that due to their electrostatic capacity. This excess charge is taken up more slowly than the condenser charge proper, and the phenomenon, known as condenser absorption, must be allowed for in all capacity measurements.

The absorption of a given condenser may be measured as follows: A condenser, F_2, whose absorption is to be measured, is connected up with a standard condenser, F_1, and resistances and a galvanometer, all as shown in Fig. 192. A balance is obtained in the same way that is employed in measuring capacity, but when obtained, it does not indicate that F_1 is to F_2 as R_2 is to R_1, as a portion of the charge, Q, that has been put into F_2 has been absorbed. If the quantity absorbed is designated by q, the potential at F_2's terminals is that caused by the charge $Q - q$. To determine q the battery key K_1 is closed and the ratio of the two resistances adjusted, so that when the key K_2 is depressed the galvanometer gives a small deflection. If K_1 is then opened and a few seconds are allowed to elapse, a deflection will be observed on closing K, which deflection should be opposite to the former one. By further adjusting the ratio R_1 to R_2, the two deflections can be made equal, whereupon q is the quantity of electricity that would cause either of the deflections. The value of q may then be readily determined by the direct deflection method.

CHAPTER X.

MEASUREMENT OF INDUCTANCE.

As has been previously noted, inductance, or more properly, the coefficient of inductance, may be either that of a given conductor or that between a plurality of conductors. The electromotive force set up in any circuit because of its inductance is the product of the coefficient of induction L and the rate at which the current flowing changes.

If, with an alternating current whose intensity and direction vary according to the sine law, we take the instant at which the current strength is a maximum, we have chosen a time when the strength is neither increasing nor decreasing, and the E.M.F. of self-induction is therefore zero. If the time is that at which the current is passing from a positive to a negative sign, the rate of current change is a maximum, and the E.M.F. of induction likewise maximum. Analogous conditions hold for the whole cycle of current changes, the result being that the E.M.F. caused by induction follows the shape of the current curve, but differs from it in phase, in that the E.M.F. is zero when the current is a maximum and *vice versa.*

As the E.M.F. so set up opposes any change in the E.M.F. that causes the energizing current to flow, a lesser current will evidently pass through a given inductive circuit if the current is alternating, that is, constantly changing in value and direction, than if it is direct and has a constant value and direction. The resistance in the latter event is a purely ohmic one which may be measured by any of the methods described in Chapter V. The resistance to the flow of an alternating current may likewise be measured by observing the amount of current that is passing and simultaneously reading the drop across the coil terminals by means of a static voltmeter. With this value and the true ohmic resistance known, the induction can be calculated, as is evident from the following:

As by Ohm's law, the E.M.F. causing the flow of current through an ohmic resistance must change with any current change, the E.M.F. and current for this component of the total resistance or "impedance" offered by the coil are in phase. On the other hand, as above explained, the E.M.F. due to the inductance of the circuit is a maximum when the current strength is zero, that is, it is one quarter of a period, 90 degrees, or a right angle behind the current. The effects of the two may therefore be graphically represented by two sides of a right-angled triangle, as in Fig. 196, in which RI is drawn of a length possessing the number of scalar units equal to the drop in E.M.F. due to the ohmic resistance, and $L \omega I$ to the same scale represents the drop due to the inductive resistance, while the length of the remaining side of the triangle represents the total impedance. RI may be determined by measuring the ohmic resistance with direct current flowing, and the hypothenuse of the triangle, which is, of course, equal to $I\sqrt{R^2 + L^2 \omega^2}$, by measuring the current that passes when alternating current is applied and the drop across the coil terminals, simultaneously. In both R is the ohmic resistance, I the current, and L the coefficient of self-induction. ω is equal to $2\ \pi$ times the frequency of the supply circuit. The value of any two sides of the triangle being known, that of the remaining one may be readily calculated.

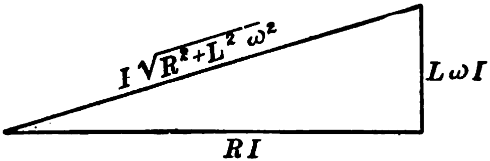

FIG. 196.

INDUCTANCE BY THE BRIDGE METHOD.

In this the coil whose inductance is to be measured, a galvanometer, a set of non-inductive resistances, a battery, and ballistic galvanometer are connected up as shown in Fig. 197. All of the resistances must be of the type described on page 241, free from inductance and capacity, and R_1 must be capable of very exact adjustment which, if necessary, may be accomplished by shunting it with a second adjustable resistance. The resistances of the ratio arms of the bridge A and B are made alike, and the value of the rheostat arm R_1 adjusted until the galvanometer shows no deflection when first the battery key and then the galvanometer key are closed. Thereupon the galvanometer key is first depressed and then the battery key, which will cause a deflection or rather throw D_1 of the galvanometer due to the inductance of S. This deflection is noted. The value of R_1 is then changed by a known amount, and the steady deflection, which we will designate as D_2 that is then given when both battery and galvanometer keys are kept closed, is noted. If now the time of vibration of the movable element of the galvanometer determined as described on page 234, be called T, and λ is the logarithmic decrement of the instrument, and if the difference between the initial and final values of R_1 is r, the inductance can be calculated from the equation

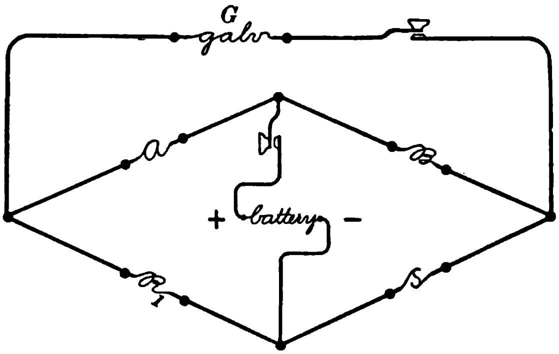

Fig. 197.

$$L = \frac{r\,D_2}{D_1} \times \frac{T}{2\pi} \times \left(1 + \frac{\lambda}{2}\right).$$

In the above, D_1 is the galvanometer throw first observed, and D_2 the second one noted under like conditions.

MAXWELL'S METHOD.

In this the inductance is found by comparison with the capacity of a standard condenser. Connections are made as shown in Fig. 198, in which Q is the inductive coil and S a standard condenser. The resistances in the arms P, R, and S must be without inductance and without capacity. To make a measurement, the value of P is first varied until the galvanometer shows no deflection with the battery key and its own key kept closed. The battery circuit is then made and broken, whereupon it will be found as a rule that the galvanometer gives a throw each time.

The resistance R is then varied until the battery circuit may be interrupted without producing a galvanometer throw, and the key again closed and held in order to see whether there is any steady deflection of the galvanometer needle. If there is, the process must be repeated until such values of P and R are reached that there is no galvanometer deflection under either condition. The value of the inductance is then found from the equation

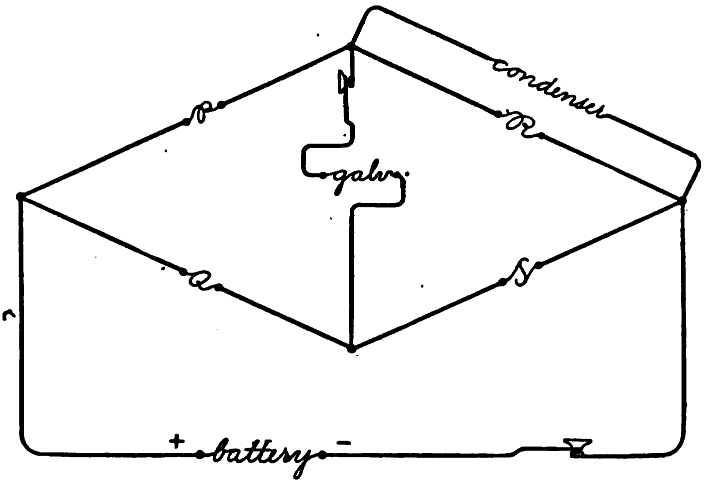

FIG. 198.

$$\frac{L}{Q} = RC \quad \text{or} \quad L = QRC.$$

Modified Maxwell Method.

In this method, proposed by Russell (see *London Electrician*, May 4, 1894), the connections are the same as in the original Maxwell one, but the condenser S is of the adjustable pattern, by means of which varying known capacities may be inserted. P is varied so that the galvanometer shows no deflection with a steady current flowing, and the battery circuit is then made and broken with its key in the regular way. If the condenser is now attached and its value varied, it will be possible to find two values of condenser capacities, the one of which will give a throw in one direction on opening or closing the battery circuit and the other in the reverse direction. By interpolation between the extent of these throws we can calculate the value of the capacity which would reduce the deflection to zero. Calling this value C, the inductance L may be calculated from the formula $L = QRC$.

COMPARISON METHODS.

The value of an unknown inductance may be determined in terms of a known one by using the connections and apparatus shown in Fig. 199. In this the galvanometer need not be of the ballistic pattern. S_1 is the known coil, and S_2 the one whose inductance is to be measured. Auxiliary resistances, R_1 and R_2, are connected in series with each, and these groups are interconnected with other resistances, a battery and a battery key, a galvanometer and a galvanometer key, as the figure shows.

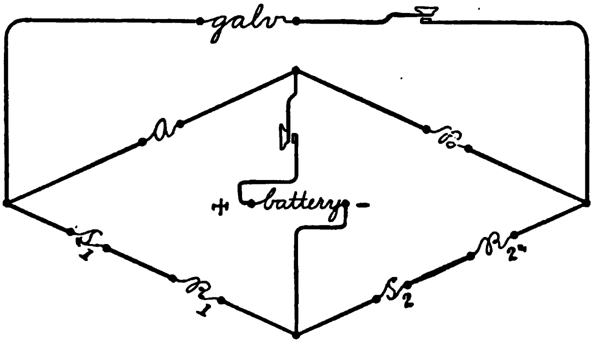

FIG. 199.

Keeping B and R_2 alike, and of fairly high value, say 1,000 ohms each, the ratio of A to R_1 may be varied, so that the galvanometer shows no deflection whether its key and the battery key are kept closed or the former closed and the latter tapped. When this adjustment is reached, $S_2 = \frac{S_1 B}{A}$.

SECOHMETER METHOD.

The secohmeter is a mechanically driven commutator, illustrated in Fig. 200, which is provided with two pairs of brushes, one of which makes contact with the terminals of a galvanometer and the other with the source of E.M.F. under measurement. When the commutator is set in rotation, it reverses the direction of the battery current through the circuit and simultaneously reverses the connections of the galvanometer to the circuit, so that the effort on the galvanometer needle is always exerted in one direction and a steady deflection maintained in spite of the current reversals through the circuit under test. With the aid of this piece of apparatus, an unknown inductance can be measured in terms of a known one by the following method (due to Maxwell). In Fig. 201, S is the standard inductance, S_1 the unknown inductance, and R and R_1 two adjustable non-inductive resistances. When the secohmeter handle is turned, the battery circuit being closed, the ratio of R to R_1 may be adjusted until the galvanometer shows no deflection. If the same adjustment is such that there is no galvanometer deflection when the secohmeter commutator is at rest, $S_1 = \frac{SR_1}{R}$.

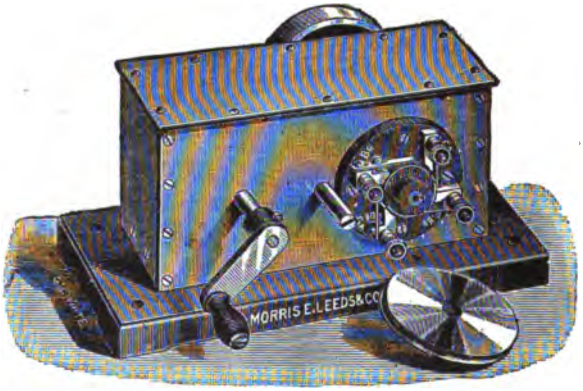

FIG. 200.

INDUCTANCE WITH ADJUSTABLE STANDARDS.

If the variable standard self-inductance described and illustrated on page 36 be used in place of the single value standard S in the preceding paragraph, the measurement becomes simplified, since after adjusting R and R_1 so that there is no galvanometer deflection with a steady current it is only necessary to set the secohmeter in operation and turn the button on the adjustable standard until the galvanometer is again at zero, whereupon the unknown inductance may be calculated from the formula $\frac{S}{S_1} = \frac{R}{R_1}$ already given.

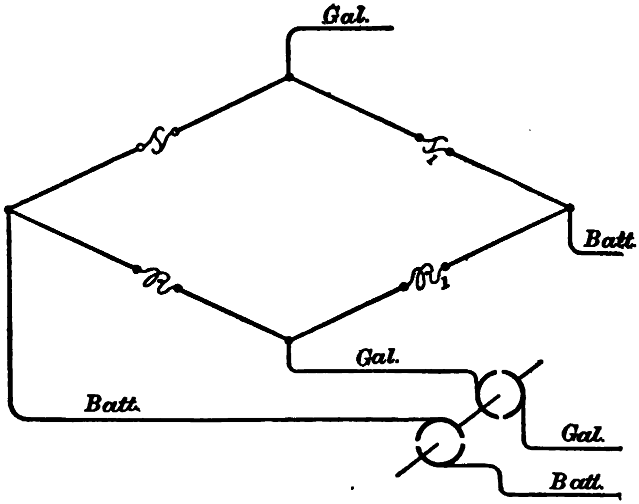

FIG. 201.

INDUCTANCE BY CALCULATION.

In a few instances, with suitably shaped coils, inductance may be obtained with a fair degree of accuracy by calculation. The simplest case is when the inductance is in the shape of a conductor coiled up to make a solenoid whose diameter is small as compared with its length. With such a coil the value of the inductance is

$$L = \frac{4\pi^2 n^2 r^2}{l}$$

in which n is the number of turns of wire, r is the mean radius of the turns in centimeters, and l the over-all length in centimeters. This formula is theoretically applicable only to solenoids of infinite length, but the error introduced when applying it to solenoids having a length of at least ten times their diameter is negligible for many practical purposes.

MUTUAL INDUCTANCE.

NICHOLS METHOD.

The quantity of electricity that is momentarily discharged through a circuit connecting the terminals of a coil inductively influenced by a neighboring current carrying coil, varies in direct proportion to the strength of the current through the influencing coil and inversely as the resistance in its own circuit.

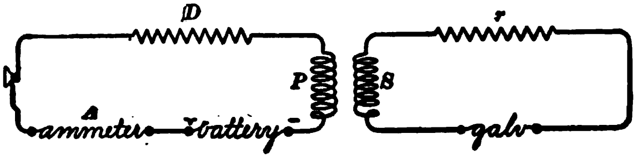

FIG. 202.

It is also dependent upon the mutual inductance between the coils; in other words, the relationship is $Q = \frac{MI}{R}$ where Q is the quantity of electricity momentarily flowing through the influenced coil, R the resistance of that coil, I the current that has been caused to flow through the other coil, and M the coefficient of mutual inductance.

To measure mutual inductance utilizing this formula, connections are made as in Fig. 202. Here P is the coil through which battery current is passed, and S the one in which current is induced when the strength of that in the former is varied.

The value of Q in the formula must be determined from the characteristics of the galvanometer employed. These characteristics are preferably found by charging a condenser of known capacity with a standard cell and then discharging this through the instrument, as before described. I is measured by an ordinary direct current ammeter, A, inserted in the primary circuit as shown, and the value of the current is adjusted at will with the aid of the resistance D. R in the formula is the resistance of the whole secondary circuit, including the galvanometer and adjustable resistance r, and may be measured by any of the conventional methods already described.

The ammeter, A, for measuring the current in the primary circuit should be of low range; in fact, if the current values employed are reckoned in milliamperes the results will be in millihenrys, which is the unit usually employed.

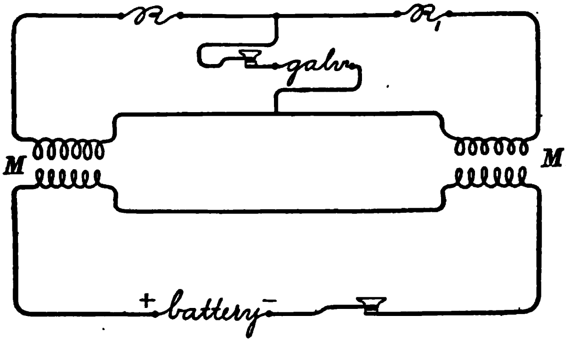

FIG. 203.

MAXWELL'S METHOD.

This involves the use of a standard of mutual inductance, and the test is made as shown in Fig. 203, in which R and R_1 are adjustable resistances and M the standard pair of coils. The values of the resistances are varied until the galvanometer shows no deflection when the battery circuit is rapidly made and broken, at which time the ratio $M : M_1 :: R : R_1$ holds good.

In making this test great care must be taken to separate the standard and unknown inductances by a distance sufficient to prevent any possibility of mutual interference by their own mutually inductive actions.

CAREY-FOSTER METHOD.

If a pair of coils whose mutual inductance is to be determined, a pair of adjustable resistances, a galvanometer, an adjustable condenser, a battery, and a key are interconnected as shown in

Fig. 204, we have another method of measuring mutual inductance. The ratio of R to R_1 and the value of the capacity, C, must be adjusted until there is no galvanometer deflection whether the battery circuit is held closed or whether it is being rapidly made and broken. When this condition is attained, the mutual induction may be calculated from the formula $M = CRr$, where r is the resistance of R_1 plus that of e. (See *Phil. Mag.* Vol. XXIII, p. 121.)

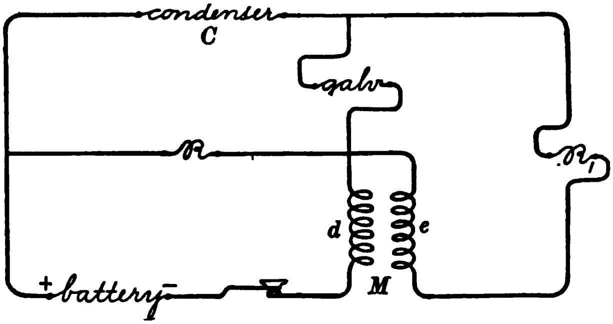

FIG. 204.

CHAPTER XI.

MISCELLANEOUS DETERMINATIONS.

WAVE FORMS.

THE determination of the curves depicting the rate of variation in strength and direction of the E.M.F. and current from an alternating source is often of considerable importance, particularly as affecting the design of auxiliary appliances. Such curves are not obtainable from apparatus ordinarily forming part of an engineer's equipment, but may be derived in the following ways:

Contact Methods.

One method of obtaining the E.M.F. curve of a given alternating current dynamo is to rigidly attach a disk of insulating material, as diagrammatically shown in Fig. 205, to the armature shaft, so that it rotates at the same speed and maintains a fixed position relative to the armature windings. On the periphery of this disk there is located a metal block connected to the windings, and a brush arranged to bear on the disk makes contact with the block once in every revolution of the armature. If the brush is held fixed, the difference of potential between it and the other terminal of the armature winding is, at the instant of contact, that generated by the coil when it is in the position

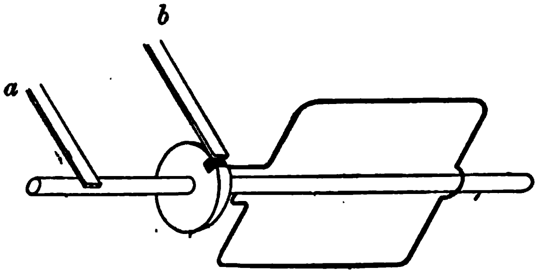

FIG. 205.

relative to the pole pieces corresponding to the brush position. As this potential is applied to the brush several times per second with machines of the usual commercial frequencies, and always in the same direction, its value may be read off from the indications of an ordinary direct current voltmeter connected between the brushes *a* and *b*, in Fig. 205. By rotating the contact brush to different angular positions around the armature shaft, the E.M.F. values may therefore be determined for any position of the armature conductors and the values thus obtained plotted so as to give the curve required.

A convenient device for making contact at various angular positions of the armature is the Fessenden portable contact maker, shown in Fig. 206. This consists of a hard rubber disk provided with a pointed spindle which is pressed against the end of the armature shaft like an ordinary tachometer. The handle shown is secured to the frame carrying the brushes and terminals, and the angle at which contact is being made is read off from the position of the scale relative to the pointer-like end of the rod carrying the heavy steadying bob.

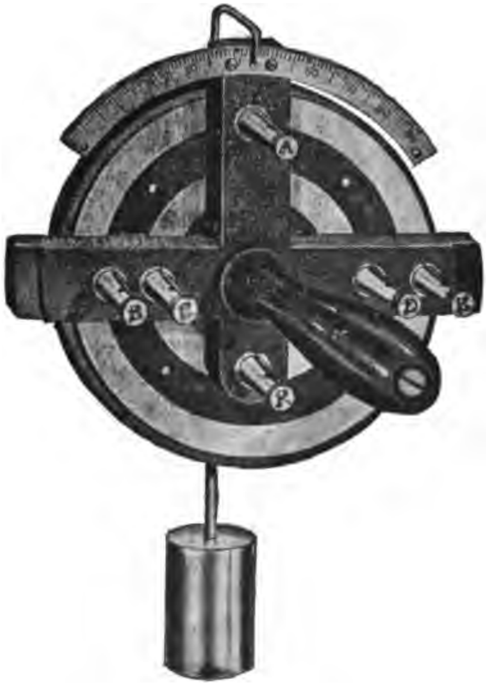

FIG. 206.

In order that the indications of a voltmeter used with a device like the foregoing may be rigorously correct, it is necessary that the same be of a type which does not draw current from the circuit, a fact which at once suggests the use of a potentiometer method, that is to say, balancing the unknown potential against an opposing known one.

To do this with a regular potentiometer, a contact maker, and the necessary accessories, and to plot the observed readings on section paper, is, however, a tedious procedure; in fact, it may require some hours if the current being investigated is not of a smooth wave form. The following instrument was devised for the purpose of minimizing this objection.

Rosa Curve Tracer.

The plan employed in the Rosa curve tracer is shown in Fig. 207, the apparatus being in this case connected up to record a current curve. *AB* is a non-inductive resistance of known value connected in series in the line under test, *CM* is a contact maker, *MN* is a resistance wire wound on and supported by an insulating cylinder, *P* is a contact brush sliding over *NM*, and *Q* is a permanent connection to *B*, the galvanometer *G* being inserted in that circuit. Current is supplied by a battery *B* having a potential that is indicated by the voltmeter *Vm.* The frame carrying the sliding contact *P*, by means of which contact may be made at any portion of the wire resistance forming the coil *MN*, carries also the point *F*, which makes the record. *D* is a drum to which the record chart is secured.

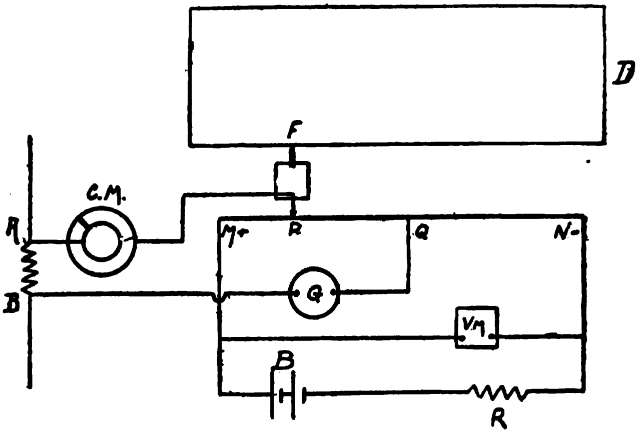

FIG. 207.

With any given load on the circuit under test, the contact *P* may be placed at some point on the wire *MN* where the galvanometer *G* will show no deflection. At this time the difference of potential between *P* and *Q* is evidently the same as that between *A* and *B*, and is therefore the instantaneous value of the impressed current with the position of the contact brush that at the time of making the reading. If the brush angle is now changed, *P* must be moved in order to bring the galvanometer to zero once more, and this operation must be repeated for each angular position of the brush. For that portion of the current curve in which the current is flowing in a reversed direction through *AB*, *P* must be placed on the other side of *Q* from that shown in order to obtain a balance. The pointer *F* does not bear continuously on the chart, but is struck against it by means of a bar, and thus makes a dot for each reading. When the lever that operates the bar is being returned to its first position, it works a ratchet that rotates the paper drum the proper distance ahead, and at the same time closes a circuit that energizes an electromagnet forming part of the contact maker, which in that

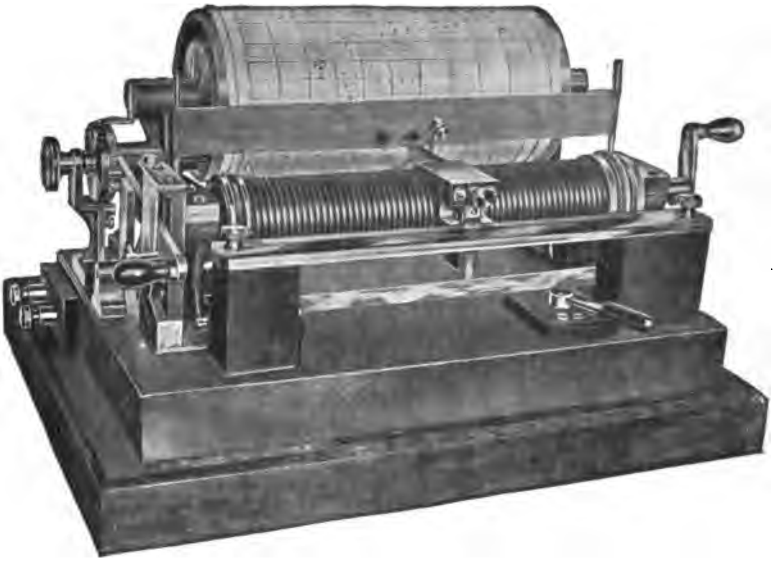

FIG. 208.

way has its contact brush advanced a corresponding amount, leaving everything ready for the next reading. The operation is therefore reduced to the simple act of moving the contact along until the galvanometer shows no deflection, raising and lowering a lever, and repeating. It is claimed that twenty points a minute can be printed by an experienced operator.

The curve tracer is shown in Fig. 208. The crank at the right is turned to cause the contact P to travel along its wire, and the lever at the left is the one used for printing, etc. The contact maker is shown in Fig. 209.

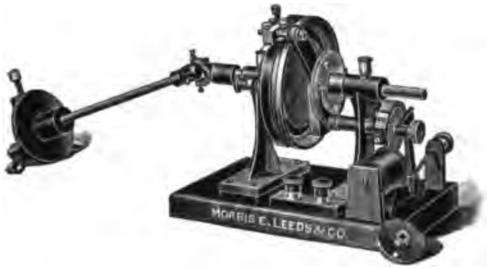

FIG. 209.

Instead of using a potentiometer method, the instantaneous values of a fluctuating current at various points on the curve may be satisfactorily determined with the aid of a contact maker, a condenser, and a galvanometer.

Referring to Fig. 210, the E.M.F. at the instant of contact is used to charge the condenser C of known capacity. Subsequently the key N is depressed, and the deflection of the galvanometer G noted. The throw of the galvanometer is of course proportional to the condenser charge, and the latter to the charging E.M.F., so that the throws are proportional to the instantaneous potentials at the different positions of the contact brush.

The Blondel contactor shown in Fig. 211 simplifies making this test. An inspection of the figure will show that if the disk D rotates in synchronism with the source of supply, contact is first made so that the condenser is charged by the E.M.F. at the point of rotation of the armature determined by the setting of the brush, and that the condenser is immediately afterward discharged through the galvanometer. The impulses thus sent follow one another with such rapidity that the galvanometer deflection becomes a steady one, and there is therefore nothing to do but set the contact maker at different angles, and observe the deflections due to each in order to obtain the relative values of the ordinates at different points on the curve.

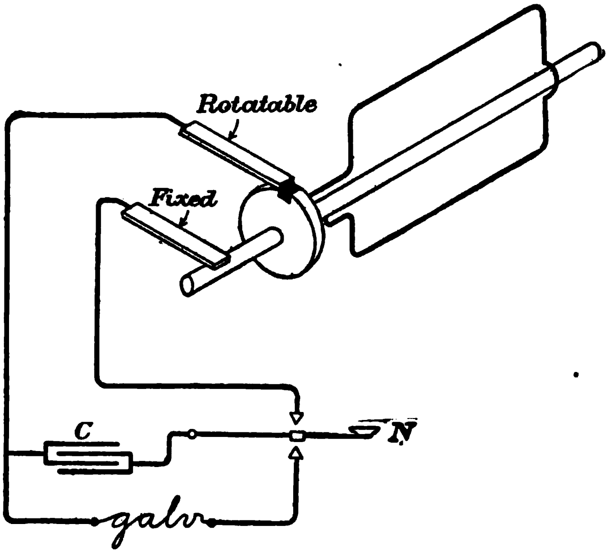

FIG. 210.

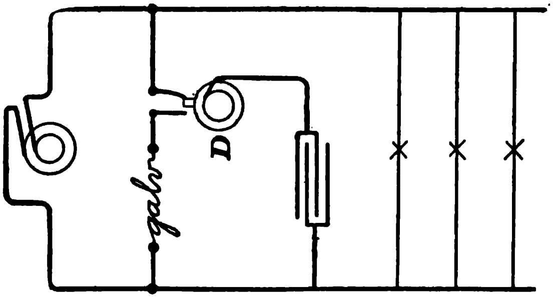

FIG. 211.

Duddell Oscillograph.

This instrument, illustrated by Fig. 212, is one in which one or more strips of conducting material traversed by the currents whose wave forms are to be determined are placed in an extremely powerful magnetic field. The latter is furnished by a circular electromagnet having its poles shaped so as to give a very narrow and intense field, and energized by several separate sets of coils, in order that by interconnecting them in different ways the necessary exciting current may be obtained from circuits of different E.M.F.'s. In the apparatus illustrated there are three mirrors similar to those used in ordinary galvanometers, but smaller and lighter. One is stationary and furnishes a reference line. Each of the other two is attached to a pair of metal strips electrically connected at their lower extremities, and held in tension by the adjustable spring arrangement shown projecting above the rest of the instrument. The path of the current is up one and down the other strip of a pair in each case. Owing to the tension of the strips the time required for a complete oscillation of a mirror is exceedingly small, namely, about .0001 second. When current is sent through either of the pair of strips, the reaction between that current and the field causes the attached mirror to deflect an amount

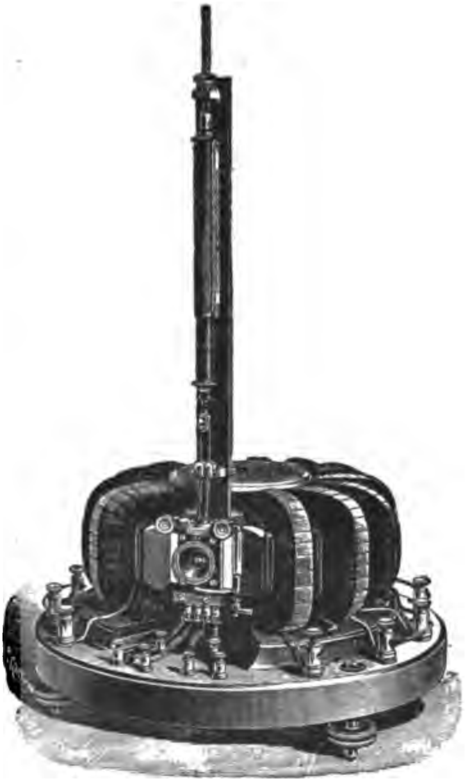

FIG. 212.

proportional to the current strength, and because the period of vibration is so small, the mirror position may continuously vary with a changing current strength, and follow it exactly. If the beam of light from the mirror were simply projected on a translucent scale plate, the visible result would be merely a straight luminous band on the plate. When, however, the light beam is first thrown on a mirror that is oscillated by a cam synchronously driven, and whose axis is at right angles to that of the oscillograph, the ray traces on the surface to which it is reflected, a curve which is, of course, the current curve. Owing to the rapidity with which the successive values in each curve are repeated and follow one another, persistence of vision causes the observer to see on the screen a curve which is the current curve. As the fixed mirror shows a straight line under the same conditions, we have all the information that is necessary in order to be able to observe the character of any current. Where records of this are to be kept, it is a simple matter to substitute a photographic plate for the screen.

The object in having two sets of strips each with its attached mirror is to enable one instrument to show on a scale or record on photographic paper, simultaneously, the varying values of both the potential and current curves of any circuit. This form is called the "Double Oscillograph."

Hotchkiss Oscillograph.

In this instrument the stationary magnetic field is furnished by a powerful laminated permanent magnet, and instead of having movable strips through which the current flows, stationary coils are provided inside of which again there are located minute soft iron needles suspended by quartz fibers. It is plain that this instrument is merely a special form of Thompson galvanometer, just as the Duddell oscillograph is merely a special form of d'Arsonval galvanometer.

The dimensions of the movable iron needles in the Hotchkiss device are so small that the period of oscillation of the systems formed of these and their respective mirrors is about the same as the moving system of the Duddell device, that is, .0001 second.

One of the double oscillographs of this pattern is shown in plan and elevation by Fig. 213, the two moving systems being, as shown, in two independent magnetic fields instead of one common one. The rectilinear deflections of the mirrors are translated into curves showing the current strength variations, by using a synchronous motor driven mirror, as in the Duddell oscillograph.

FREQUENCY METERS.

Hartmann and Braun Frequency Meters.

If an electromagnet be excited by an alternating current, and a tuning fork is presented to one pole of this magnet, the successive attractions will set the tuning fork in vibration if the period of the fork is the same as that of the alternations, but the fork will not respond if this sympathy does not exist. The Hartmann and Braun frequency meter takes advantage of this fact. Referring to Fig. 214, showing a switchboard pattern of such a device, the twelve white rectangular patches appearing in the two openings cut in the dial plate are the ends of steel strips or reeds bent over at right angles to the length of the strips proper and painted white to make them more conspicuous. Opposite each reed there will be noticed a numeral, 100.5, 101,

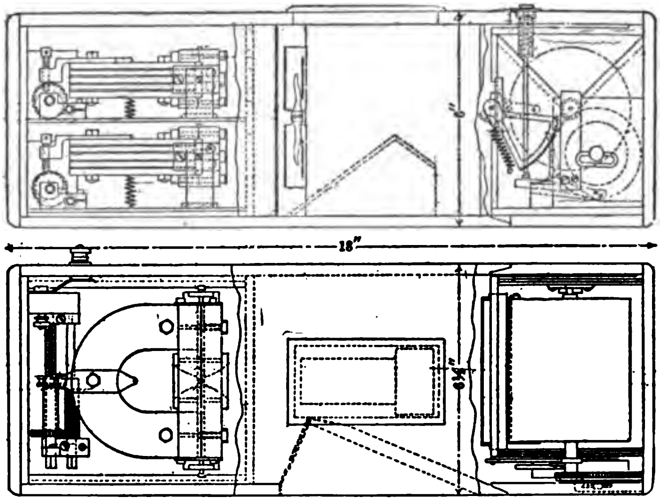

FIG. 213.

101.5, etc., these being their respective vibration rates in alternations per second. Between the two rows of reeds is a laminated core electromagnet (not visible in the illustration) through whose windings is passed the alternating current whose frequency is to be measured. Evidently now if, as shown by the cut, the end of reed 98.5 vibrates over its full amplitude, the ninety-eight and ninety-nine reeds at the same time vibrating slightly, the current impulses follow one another at intervals corresponding to the vibration period of reed 98.5, that is to say its frequency is 98.5 alternations per second.

Instead of visually noting which of a series of reeds of different periods is vibrating over a maximum amplitude, the accoustic properties of such strips may be utilized, provided that their rate is one giving a note that is audible to the human ear, namely between fifty and one hundred and fifty vibrations per second.

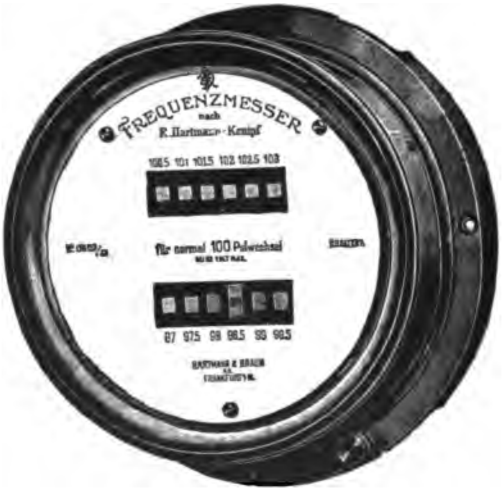

FIG. 214.

A Hartmann and Braun instrument of this kind, with its outer casing removed to show the arrangement of the mechanism, is illustrated in Fig. 215. The various reeds, in this case of periods from 79 to 110 inclusive, are arranged on a circular framework which may be rotated by means of the central handle so as to successively present them to the magnet system.

This system is composed of two magnets which when brought together by means of the handles shown act as one. The double magnet arrangement is convenient in that, after the frequency of the circuit under test has been determined by rotating the central button until a note of maximum volume is heard, the magnets may be separated and the otherwise continuous sound which might be annoying, stopped.

They still perform a useful service, however, as if the frequency of the circuit should either increase or decrease, one or the other of the magnets would set its corresponding reed in vibration and the note then heard serves as a warning of the change.

In both the visual and acoustic types of meters the range of measurement may be doubled, or rather each reed may be made to respond to a frequency double that of its normal one by adding either a few turns of direct current exciting winding or by inserting a permanent magnet to polarize the reeds.

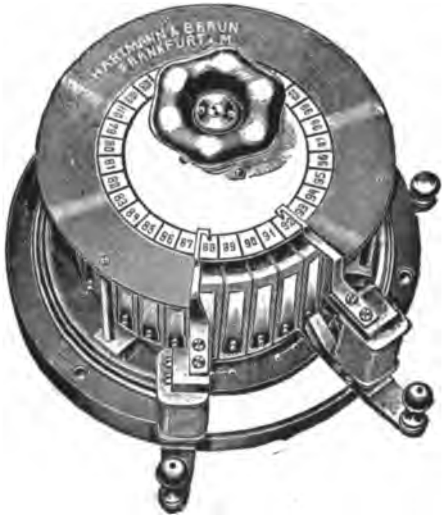

FIG. 215.

This follows, as a non-polarized strip is evidently attracted by each current impulse irrespective of direction of the alternating current flow, whereas if a strip be polarized magnetically the current flow in one direction attracts and that in the reverse direction repels it, and there is hence required double the original frequency to give the same number of attractive efforts.

The accuracy of these instruments is extremely good, and their simplicity and the absence of what in the accepted sense of the term are moving parts commends them for general service.

Schmidt Frequency Meter.

Another acoustic device for measuring the frequency of alternating currents is that due to K. E. F. Schmidt.

In it the current under investigation is passed through a telephone receiver and the diaphragm of that receiver placed before the open end of a tube about one inch distant therefrom. The tube is about one inch in diameter and two or three feet long, and has within it a piston which may be moved backward and forward by means of a handle so as to vary the effective tube length. The vibrations of the receiver diaphragm tend to set the air imprisoned in the tube into vibration also, and if the piston is moved in and out, a position can be found where the tone emitted by the tube is of a maximum volume. The vibration periods of the diaphragm and the air column are then alike, and hence the frequency may be read off directly from a scale properly marked on the piston rod.

Manzetti Frequency Meter.

In this instrument there is a moving system which consists of a copper disk mounted rigidly on the same axis with a parallelopiped of laminated iron. This element is either pivoted or carried by a quartz fiber, and the copper and iron used therein are acted upon by separate sets of coils. The two sets of coils are connected across the circuit with a resistance in series with each pair. When current flows, the turning effort exerted on the iron is independent of the frequency, while in the copper disk it is a function of the frequency. If, therefore, the two sets of coils are adjusted so that at the standard frequency the torques exerted by them are equal and opposite, there will, of course, be no deflection, but if the frequency changes, a deflection will be produced because of the different torque then exerted by the copper disk. This torque can be measured either on the dynamometer principle mentioned on page 165, or may be used to urge a needle over an appropriate scale against a constantly increasing spring pressure. In the latter event the scale may be calibrated so as to indicate frequencies directly.

Westinghouse Frequency Indicator.

This instrument is illustrated in Fig. 216, and consists of two voltmeter movements so connected together mechanically that they tend to move the pointer in opposite directions. In series with one of the movements there is a non-inductive resistance, and in series with the other, a resistance that is highly inductive. If the frequency changes, the torque exerted by the two windings will therefore become unbalanced, that of the inductive winding being relatively decreased, and if, as is the case, the construction of the apparatus is such that when the needle swings in either direction, the torque of the member tending to swing it in opposite direction is increased, it will evidently move until the two forces are again balanced. The scale is empirically graduated by passing currents of known frequency through the device and marking on the scale the different positions assumed by the needle. The indications of these instruments are influenced by wave form as well as frequency, and they are hence correct only on the wave form for which they are adjusted.

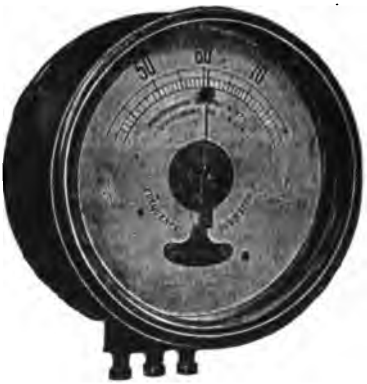

Fig. 216.

PHASE INDICATORS.

Two alternating currents of like frequency are said to differ in phase when they do not simultaneously attain their respective maximum positive, maximum negative, and zero values. The difference in phase is usually expressed in terms of the cosine of the angle ϕ between the two radii passing through the corresponding zero values, when the circumference of a circle whose perimeter is one wave length is used as the reference line. This expression for phase difference is rigorously correct only when the currents are sinusoidal, and not, as is frequently the case in practice, when they are of different wave forms.

Assuming sine waves, we would have in an alternating current circuit in which there is a difference in phase between the potential and current curves, the expression $P = E I \cos \phi$ in which E and I are the effective potential and current as measured by a voltmeter and ammeter of the static, hot wire, or electromagnetic type before described, and P is the power.

Phase meters are instruments for indicating the value of the angle ϕ.

Voltmeter, Ammeter, and Wattmeter Method.

If the difference in phase between the current and potential curves in an alternating current circuit is desired, one way to determine it is to use a wattmeter, and in addition to insert a voltmeter and an ammeter in the line. If all three readings are observed simultaneously, the cosine of the angle of lag may be calculated from the formula $P = E I \cos \phi$ mentioned above, all of the factors with the exception of $\cos \phi$ being known from the observation.

Oscillograph Method.

The double oscillographs described on page 264 may be used to determine the difference in phase between two alternating currents, by passing one through one of the movable elements of this apparatus and the other through the other. If the resultant figures are thrown on a translucent plate or are photographed, two curves will appear together with the zero or reference line made by the fixed mirror, and the difference in phase can be scaled off therefrom. Oscillographs are but seldom available, however, so that this method is in very restricted use.

Dobrowolsky Phase Indicator.

This is an instrument in which a pointer sweeping over a graduated scale shows directly the difference in phase between two currents. Referring to Fig. 217, the movable element to which the pointer is attached is a disk of soft iron pivoted at its center and having its motion opposed by a volute spring. If the current through the two sets of windings shown as surrounding the disk at right angles to one another are in phase, no force will be exerted to rotate the disk. If, however, a phase difference exists, there is set up a rotary magnetic field, which in turn exerts a torque on the disk and tends to turn it. If the changes in strength of one current lag behind those of the other, the torque will be in one direction, and if *vice versa* the needle will be oppositely rotated. The instrument, after being calibrated with known phase differences, will therefore indicate not only the difference in phase, but which current is leading and which is lagging.

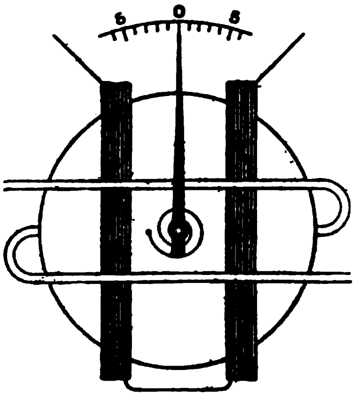

FIG. 217.

If the instrument is being used on a circuit in which both the frequency and the effective potential are constant, the scale graduation may be made to show either the effective amperage or the wattless current — that is, the component of the total current that is not effective in doing work — flowing through it. An instrument so graduated is frequently convenient for use in central stations.

Hartmann and Braun Phase Indicator.

This instrument is somewhat similar to an indicating wattmeter, having a stationary coil through which the whole current to be measured is passed. The movable element, however, instead of consisting of but one fine wire coil, consists of two such mounted with their planes at right angles, and supported above and below by pivots.

Current is led into and out of these windings through flexible silver strips so fine that no appreciable force prevents the needle attached to the coil pair from assuming any position within the limit of its travel. One of the instruments is shown in Fig. 218. In series with one of the two movable coils there is placed a non-inductive resistance, and the other coil has in series with it a highly inductive resistance, as is indicated by the two spools mounted on the transformer-like core. The non-inductive resistance and its spool are connected in parallel with the inductive resistance and its spool, a non-inductive resistance being placed in series with the pair to cut down the applied potential. Owing to the presence of an inductance in one coil circuit and the fact that there is none in the other, the currents in the two differ in phase by ninety degrees. These displaced currents set up a rotary field, which in turn is located within the influence of the field due to the current through the stationary winding. When, therefore, the current through the series coil differs in phase from that flowing through the potential coils by a given amount, the potential coils will assume one fixed position where the rotative effort is zero. When the phase difference between two currents changes, however, the angle of the double coil movable element relative to the fixed one must change also. The scale over which the needle of this instrument swings may therefore be graduated empirically to indicate phase difference.

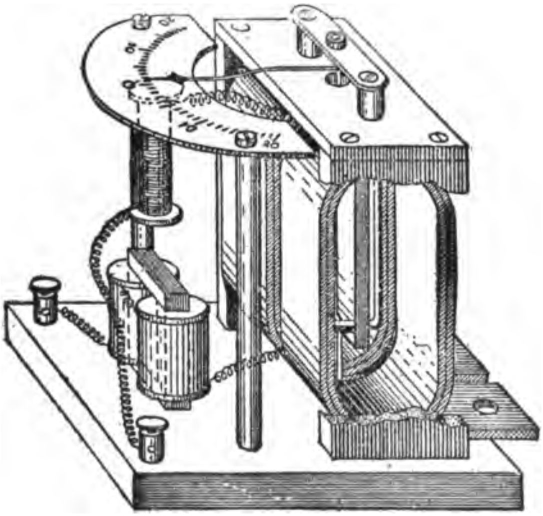

FIG. 218.

It should be noted that while this form of device is independent of the amount of current flowing and of the E.M.F. applied, it is dependent on the frequency and must be specially calibrated for each frequency, if correct results are to be had.

SYNCHRONISM INDICATORS.

In order that two sources of alternating current may be connected in parallel so as to jointly supply current to any given circuit, it is not only desirable but in many instances absolutely necessary, that some device be employed which will indicate when the current furnished by the source about to be added is in synchronism with the one already delivering current, in order that it may be connected at that time. If it were coupled in when the currents are out of phase, an interchange of current between the sources would ensue, which current may be so large as to cause disastrous results.

Lamp Synchronizers.

The simplest form of apparatus for indicating synchronism between two sources of alternating current is shown in Fig. 219. Here *G* and *G′* are the sources, *T* and *T′* transformers energized by them, and *L* and *L′* incandescent lamps. It will

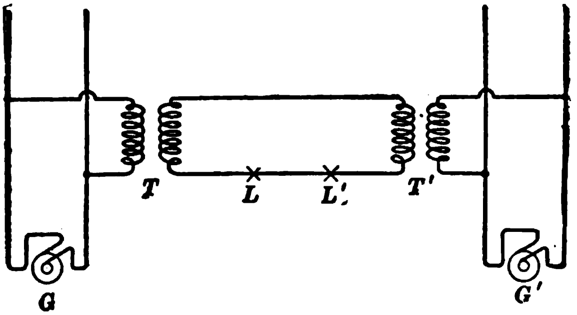

FIG. 219.

be seen that the secondary windings of the transformers are connected in series. If, now, the currents from *G* and *G′* are in phase, the current impulses of the transformer secondaries evidently increase in value simultaneously, and if they are opposite in direction, no current will flow through the lamps and these will remain dark. Should there be a difference of phase, some current will flow in the lamp circuit, and this will be a maximum when the phases are 180 degrees apart; that is to say, when the currents of the two secondaries are assisting each other. Hence, if *G* is a machine already running and *G′* is one to be thrown in, the lamps will be illuminated and extinguished in rapid succession when *G′* is first started, and these successive periods of light and darkness will succeed each other with decreasing frequency as the speed of rotation of *G′* rises until its speed is exactly that of *G* and the current delivered thereby in phase therewith, at which time the lamps will remain dark. The operation of connections in parallel may then be accomplished by closing an appropriate switch. By reversing the connections of the secondary of either one of the two transformers, the lamps will be burning at full brilliancy when synchronism is attained, instead of being extinguished at that time.

The first method is, however, preferable, as after watching lamps during the time at which *G'*'s speed is being raised to its desired value the eye becomes fatigued, and it is more difficult to determine the instant of maximum brilliancy than that of complete darkness.

Voltmeter Method.

If in the above plan an alternating current voltmeter is substituted for the two lamps its indications can be used to show the attainment of synchronism with greater accuracy than is possible with the lamps. As alternating-current voltmeters are of less sensibility near zero than in the working range of the scale, or in other words, as the deflection per unit of potential difference is less near zero than up the scale, it is advisable to use the second scheme of connections mentioned; that is, the one in which the transformer secondaries are connected, so that their E.M.F.'s assist each other when synchronism is attained. In using a voltmeter its indications are merely observed until the needle is practically at rest at a maximum indication, whereupon the incoming machine is coupled in as before.

The Müller Synchronism Indicator.

For commercial purposes it is desirable that the synchronizing apparatus shall show not only when synchronism between the incoming generator and the one or ones already supplying current is reached, but that it should show whether the incoming machine has too high or too low a frequency, that is, whether it is running too fast or too slow, as this enables the attendant to regulate the speed accordingly.

An instrument fulfilling these requirements is shown in Fig. 220. As illustrated, it is arranged for use on a three-phase circuit. An outer ring of laminated iron is wound about with wire and has leads tapped into its convolutions at three equidistant points. These three terminals are attached to the bus-bars. Within this ring there is a similar one provided with a shaft on which it rotates and having three collector rings so that electrical contact may be made through brushes to three leads tapped into its winding at equidistant points, as in the case of the stationary ring. The brush terminals are connected to those of the incoming machine. The rotating element carries a target or pointer, so that its movement may readily be discerned. The electrical connections are made such that the rotary magnetic fields set up by each of the rings rotate in the same direction. When, therefore, the frequency of the potentials supplied to the two windings is the same, the fields rotate in the same direction with the same velocity and no turning effort is exerted on the inner member. When the two are not in phase, however, turning effort exists, and this will rotate the target in one direction if the frequency in the inner ring is greater than that in the outer, and *vice versa* if it is less. A stationary target secured to the outer ring is used as a reference mark, the two currents being of the same frequency and also in phase when the rotating disk masks it. It should be noted that the movable disk will always remain stationary when the frequencies are the same, but that its vertical position is assumed only when the currents are also in phase. At other times the angle between the fixed

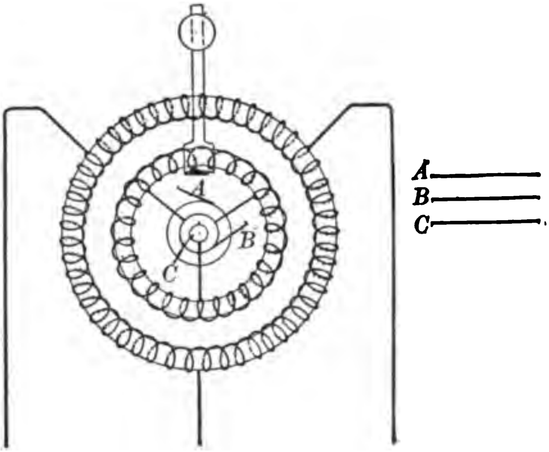

FIG. 220.

and rotary targets is a measure of the phase angle between the currents.

Lincoln Synchronizer.

In this instrument, illustrated in Fig. 221, the position of a pointer relative to a fixed mark on the dial over which it rotates shows the phase relations and difference in frequency between two alternating currents just as does the Müller instrument just described. The principle of operation is, however, somewhat different.

Referring to Fig. 222, if within the fixed coil *F* there is mounted on the freely movable shaft *C* a coil *A*, and an alternating current is passed through *A* and *F* in series, *A* will rotate until it takes up the position shown parallel to the plane of *F*. If the connections between *A* and *F* are reversed, or, which amounts to the same thing, the two are fed by currents of like frequencies differing in phase by 180 degrees, *A* will rotate 180 degrees. The force tending to carry the coil *A* into position is, under the conditions laid down, a maximum when *A* and *F* are parallel and it is zero when they are at right angles.

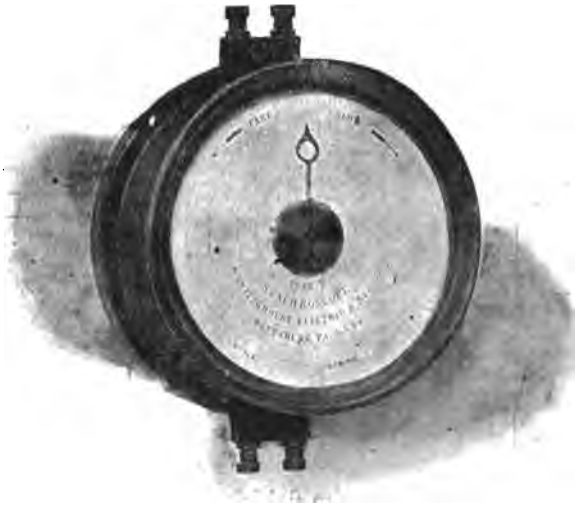

FIG. 221.

An instrument with a single coil would thus have a "dead center" position, which would not be admissible.

If, however, a second coil *B* be added, rigidly secured at right angles to the coil *A* and, by suitable means, the current in *B* is made to differ in phase from that in *A* by the same angle of 90 degrees, *B* will be in a position where it exerts a maximum torque when *A* is at its zero torque position. Hence, if there existed a difference in phase of 90 degrees between the currents in *A* and *F*, *A* would always come to rest at right angles to *F*, and if the currents in the two were in phase, *A* would turn until it was parallel to *F*. For intermediate phase differences, *A* would assume intermediate angles, and hence a pointer attached to *A* would show these differences on a dial.

In the actual instrument the coil *F* and the coils *A* and *B* are wound on laminated iron cores, forming a structure like a small motor. The difference of 90 degrees in phase between the currents in *A* and *B* is produced by putting a highly inductive resistance in series with one and a non-inductive resistance in series with the other. The currents whose phase and frequency relations are sought are, of course, led, the one through the windings of *F* and the other through the coils *A* and *B* with their respective resistances.

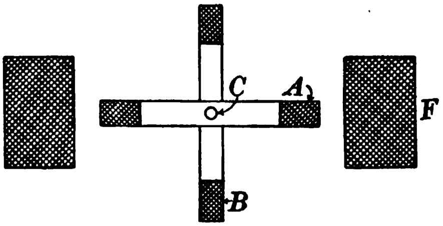

FIG. 222.

As in the case of the Müller instrument, the Lincoln synchronizer exerts a considerable torque, so that it is possible to use a robust construction with heavy bearings without introducing frictional errors.

SPEED INDICATORS.

Using a Magneto and a Voltmeter.

From the law of dynamo-electric machines the potential delivered by a given armature rotating in a magnetic field of constant strength is directly proportional to the speed of rotation of the armature. In other words, if we take a small dynamo whose field is supplied by permanent magnets, the voltage at its brushes varies directly with the speed and can be used as a measure of that speed. Fig. 223 shows such a magneto adapted to be belt driven by the shaft whose speed is to be measured. The revolution indicator used with it is simply a voltmeter, usually of one of the commercial types described on page 193 *et seq*, whose scale has been arbitrarily calibrated to show revolutions, by noting the position of the needle when the magneto is driven at various known speeds.

This method of speed indication has the advantage that the indicating element may be placed at any reasonable distance from the shaft whose speed is being observed, and that the rate of rotation is shown at each instant on a scale which may be of considerable length so that close readings can be had. It is also possible to have two or more indicating stations with the one magneto, as this involves only the addition of another voltmeter. Direction of rotation can be shown also by using a permanent magnet type voltmeter having the zero in the center of the scale, in which event the needle will deflect in one direction for a given direction of rotation of the magneto, and in the other for the other.

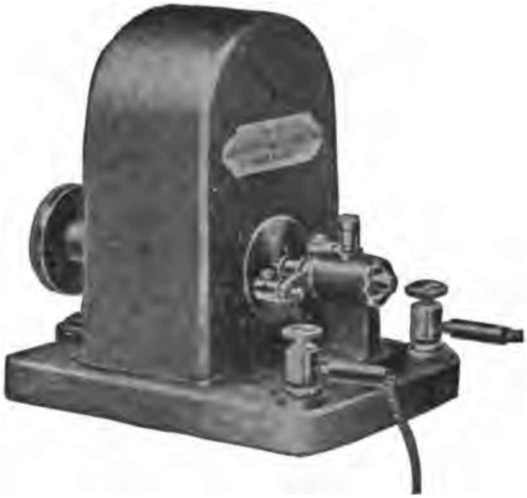

FIG. 223.

Eddy Current Revolution Indicator.

In Fig. 224 *d* is a copper cylinder mounted on a shaft running through its axis and driven by a belt from the shaft whose speed is to be measured. Pivoted co-axially within the cylinder is a soft iron needle, *n*, *s*, carrying an index *I*, that sweeps over a graduated scale. The cylinder is embraced by the polar extremities of a permanent magnet *S*, *N*. When the cylinder *d* is set in rotation, eddy currents are generated therein as it cuts the lines of force of the permanent magnet, and these currents react on the soft iron needle and tend to carry it along. The tendency of *n*, *s*, to rotate is opposed by the directive force exerted on it by the permanent magnet, the latter acting in this respect like the magnet in the Ayrton and Perry instrument mentioned on page 152. The scale is graduated empirically as in the case of the magneto and voltmeter combination above named.

Changes in strength of the field supplied by the permanent magnet affect the accuracy of the indications but slightly, because as this changes, the eddy currents in *d* changing likewise, the restraining force on the needle, *n*, *s*, changes also. Experiments show that the strength of the permanent magnet may decrease as much as twenty per cent without causing an error in indications greater than one per cent.

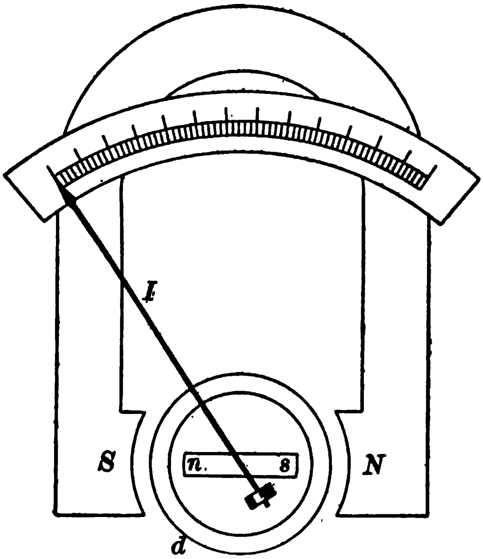

FIG. 224.

Several modifications of this form of speed indicator have been proposed.

Schollkmann Speed Indicator.

In this device a small inductor alternator is driven by the shaft whose speed of rotation is to be measured. The moving part is a simple structure of laminated iron and the stationary portion has two sets of windings wound on alternate poles. One of the sets is energized by any convenient source of direct current, such as a storage battery, and alternating currents are induced in the other by the rotating core. The current thus set up is carried through wires to the indicating instrument, which consists of a small two-phase motor. In series with one of the windings of this motor there is placed an inductance so as to cause a phase displacement and give rise to a rotary field which in turn exerts a torque on the armature, the latter being an aluminum cylinder which is rotated against the tension of a volute spring. A pointer carried by the cylinder moves over a properly divided scale which shows the speed in revolutions directly. As the indications of the indicator are dependent on the frequency and not on the potential of the current supplied to it by the generator, it is not necessary to have the direct current source for energizing the latter of constant E.M.F.

Stroboscopic Methods.

If an alternating current is used to energize a source of light, such as an arc lamp or an incandescent lamp with a thin filament, the intensity of the illumination is constantly varying as the strength of the current varies. This phenomenon is not ordinarily detected by the eye, because on commercial circuits the frequency with which the alternations succeed each other is greater than the eye can detect, whence, because of the persistence of vision, the resulting illumination appears uniform. These successive variations in illumination may, however, be used in measuring speed of rotation if the number of alternations of the supply circuit is known. A conspicuous mark, such as a streak of white paint, is made on the periphery of a pulley on the shaft whose speed is to be taken, and this mark will appear to remain stationary when illuminated by an arc lamp fed by the current named if the number of alternations and revolutions are alike, as the illumination from the arc will be a maximum at the same angular position of the mark at each revolution.

Should the apparatus whose speed is being measured be driven from a source that is not rotating in synchronism with the alternations, the times of equal illumination will occur at varying angular positions of the mark, and the latter will therefore seem to the eye to rotate at a rate that increases as the difference in speed between the two sources increases.

The source of illumination in stroboscopic methods of measuring speeds is often a spark from the secondary winding of an induction coil whose primary is excited at known intervals, usually through a contact made by a tuning-fork whose period has been determined.

TRANSFORMER TESTING.

Efficiency.

Transformers waste in themselves a certain amount of energy, so that the ratio of the electrical input to the output is not unity. The losses are the sum of the following factors: in the primary winding, the I^2R loss, this being the energy required to overcome the resistance of the primary winding; in the secondary winding, a corresponding I^2R loss; the loss due to the hysteresis of the iron forming the magnetic circuit; and finally, the eddy current losses.

The I^2R losses in both primary and secondary windings are easy of measurement. Direct current of the normal full ampere capacity of each winding may, for instance, be passed and the drop across the winding terminals simultaneously observed by using a low-reading voltmeter. The product of these values is, of course, I^2R in each case. Another way is to measure the resistance of each winding by any of the suitable methods outlined in the chapter on resistance measurements, and to multiply these values by the squares of the strengths of the currents which they are to carry.

The sum of the hysteresis and eddy current losses can be measured indirectly by measuring the input and output of the transformer by indicating wattmeters, when the difference between the indications, less the sum of the I^2R losses in the primary and secondary windings, gives the result.

Another way is to pass full normal current through either the primary or secondary winding, the secondary (or primary as the case may be) circuit remaining open at the same time, and inserting a wattmeter in the energized circuit. The wattmeter reading gives the hysteresis and eddy current losses plus the primary (or secondary) I^2R loss. The latter is measured separately, as already explained, and then deducted from the result. To have this test an accurate one, it is necessary to employ a wattmeter which will give a large scale deflection on a very low power factor, preferably one in which full scale is given with not over ten per cent of the maximum volt-ampere capacity. The instrument must also give accurate readings on these low-power factors, a requirement which excludes all types in which the angle between the fixed and movable coils is a variable, and practically limits the choice to true dynamometers in which a torsion head must be rotated manually to get a reading. The connections for the above test are given in Fig. 227.

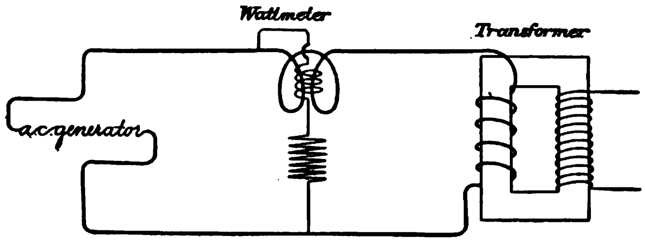

FIG. 227.

The method of testing above described is objectionable for very large transformers, as it calls for an amount of current sufficient to fully load the apparatus during the time that the test is in progress. Where it is not possible or advisable to make this heavy draught on the supply lines, Sumpner's method may be brought into play.

To make this test, two identical transformers of the size to be tested are required, and there is needed also a third transformer with a capacity sufficient to supply enough current to make up the sum of the losses of the two others, but whose efficiency is immaterial and need not be measured. Wattmeters and an ammeter all connected in circuit as shown in Fig. 228 are the instruments needed. The ammeter A^1 is not essential, and the same is the case with the voltmeter V, but these give data of interest. From the connections it will be noted that the transformers are so connected that each supplies the other with current, the small transformer receiving enough current from the mains to add to the large transformer circuit, current sufficient to overcome the losses in the transformers *A* and *B*. When the test is made, the regulating resistance *R* is varied until the ammeter *A* shows that full current is flowing through the secondary windings. The ammeter and voltmeter in the primary circuits should simultaneously show that the volume and potential of the current flowing in these is the normal maximum. The wattmeters *W* and *W′* will then give the desired information, the indications of *W* giving the sum of the iron losses in the two transformers, and *W′* the copper losses of the two plus those in the leads and in the wattmeter *W* and ammeter *A*.

Transformer Insulation Test.

One of the important tests to which every transformer should be subjected before it is placed in circuit is that to determine the insulation resistance of its windings. To have the results of any value, it is necessary that they be made with high applied potentials, as it is found that the behavior of the insulating material is entirely different under high electrical stresses than under low ones. The best test is the rough and ready one of using a source having a potential at least double that of the highest voltage to which the device will be connected in use, and then with this potential testing to see whether a breakdown can be made through the primary insulation to the core, through the secondary insulation to the core, or from the primary to the

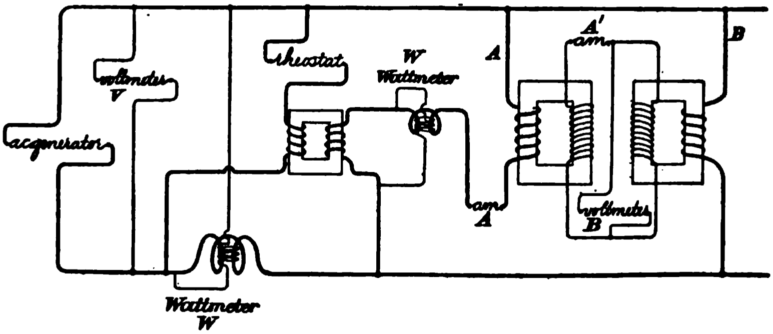

FIG. 228.

secondary winding. In an electric-lighting plant where but one potential is in use, the testing potential is easily obtained by connecting in series the fine wire windings of two or three transformers whose coarse wire windings are connected in parallel to the low-tension mains.

For general testing work a regular step-up transformer with a spark gauge is preferable.

Transformer Polarity.

If two or more transformers are to be used, connected together in series or parallel, it is necessary to know the relative instantaneous directions of the current flow in each, in order that they may not oppose each other in the first case or short circuit through each other in the second. For making this polarity test the most elementary and in the majority of cases the most satisfactory method is, in the case where the devices are connected in series, to make this series connection at random, and then attach a voltmeter to the free terminals. If then the connections are arranged so that the potentials assist each other, the voltmeter will show double the voltage indicated by the secondary of a single similar transformer, while if they are connected in opposition the voltage reading will be zero. Where the secondaries are to be connected in parallel this may also be done at random, fuses being inserted between them. If when the primary circuits are closed the fuses blow, the connections are such that the transformers are short circuited on each other. If they remain intact the coils are properly connected in parallel. In the latter test the capacity of the fuses should be from two to five per cent of the full load capacity of the transformer windings. It is necessary to allow a margin as transformers are never exactly alike, and there is always a small interchange of current even with windings properly paralleled.

General.

In all transformer tests it is advisable to place in series with the circuit through which the exciting current is passed, a fuse rated to blow at about 50 per cent greater current than the maximum full load current desired. This precaution is necessary, because when current was last passed through the transformer it has, except in the very rare instance in which it was interrupted as the current curve passed through the zero value, been cut off when the iron core was magnetized in one or the other direction. If, when current is again thrown on, the direction of the initial impulse is such that the residual magnetism of the core tends to assist instead of oppose the initial rise in current strength in the transformer winding, the current value may rise to an amount so greatly in excess of the capacity of the measuring instruments that the needles of the latter will be bent or the movements otherwise damaged. The fuse protection will generally save the instruments from this harm.

TESTING INTEGRATING METERS.

Integrating, or as they are erroneously but more commonly termed, "recording" instruments, used to measure the amount of power supplied to a consumer, form a class of electrical measuring apparatus that for various reasons requires frequent checking to determine whether or not the accuracy is still within permissible limits.

Test with Indicating Instruments.

A common method of testing an integrating meter consists in connecting in circuit with it an instrument of the indicating pattern and then putting on a steady load for a length of time measured accurately by a stop-watch. The integrating instrument is supposed to show on its dials the ampere hours (or watt hours, as the case may be), and if in calibration its indications should of course correspond with the ampere (or watt) hour rate figured from the readings of the indicating apparatus and the watch. The meter dials are seldom sufficiently subdivided to allow of an accurate reading of its indication unless the test is extended over a period of hours. As in practically all of them, however, the motion of the moving element is reduced through a train of gears, it is possible to shorten the time of the test by observing the number of revolutions made by the rotating element if the gear reduction ratio is known. A paint mark on the rotating part makes it possible to count the revolutions accurately.

Tests made with portable indicating meters have the great advantage that the integrating meter may thus be checked in place on the consumers' premises, the load being adjusted by switching on the proper number of lamps. That the meter is erected at the point where it is to be when doing its normal work is of importance for accuracy, as well as convenience, since all such devices are influenced to a considerable extent by mechanical vibrations, and a meter which would show up as correct in a test made in a quiet laboratory might register wrongly when erected on the consumers' premises. Vibration causes the moving element to jump up and down on its pivot, and the friction in this case is well known to be less than the friction existing where no vibration is present. The error is, of course, in favor of the supply company in so far as the readings are apt to be, if anything, high, but on the other hand it is approaching too closely to the comic-paper gas-meter standard if the apparatus is found to register current when none is being drawn by the consumer.

The test in place with indicating instruments, while allowing for some of the peculiar conditions in each installation, is not always feasible. For instance, in many cases the load on the meter is not steady at a given point for long intervals, but with motor loads, and particularly when these motors are driving elevators, is fluctuating violently at frequent and irregular intervals. To follow the ampere fluctuations with an ammeter or the watt fluctuations with an indicating wattmeter and simultaneously assign the correct duration period to each by referring to a stop-watch, is practically impossible. In this event if the current is continuous it is advisable to resort to the following scheme.

Testing with Electrolytic Meter.

The standard in this case becomes a voltammeter, usually of the copper pattern described on page 14. By comparing the ampere hours as shown by the gain in weight of the cathode after being in circuit for any desired period with the ampere hours shown by the dial of the integrating instrument, the accuracy of the latter can be determined offhand. As an electrolytic meter shows the product of the true average current by the time that it has been in circuit, results of a high degree of accuracy may be obtained with a fair chemical balance and a very ordinary timepiece if the period over which the test extends is made reasonably long.

If the integrating meter shows watt hours instead of ampere hours a voltmeter is needed in addition to the voltammeter, and from its indications it is necessary to derive some mean volt value which will fairly represent the mean voltage during the test. The volt approximation may be made very closely, as its extreme fluctuations are usually but a few per cent, so that the average can be ascertained to a fraction of a per cent.

Still another method involves the use of a regulation motor type integrating meter as the standard, this one being connected in circuit with the one under test, so that the attached load is simultaneously measured by both. The readings of the two must obviously agree if the calibration of the tested one is correct. The meter used as the standard is usually specially constructed so as to obtain maximum accuracy. The gear train and dials of the ordinary meter are omitted to reduce the frictional errors, and their place is taken by a pointer attached directly to the shaft of the rotating element so that its revolution may be closely observed. The bearings are often made of diamond instead of sapphire, and particular care is observed in constructing the pivots and adjusting the calibration.

Such a standard must itself be checked from time to time by comparison with an indicating instrument and a stop-watch, but this may be attended to at the station, where the facilities for such work are better than on the consumers' premises.

CHAPTER XII.

THE LOCATION OF FAULTS.

In a great many cases electrical measurements may be made to locate electrical faults, which measurements, while involving principles that have been mentioned before in this volume, appear for one reason or another somewhat out of place in the chapter setting forth their said principles.

The author therefore resorts to the subterfuge of the present "miscellaneous" chapter to describe and discuss the more common and useful of the methods which can be included in this convenient category.

While it gives a by no means complete list of the numerous expedients employed in various of the more specialized methods of testing, it is thought that the descriptions taken in connection with what has gone before will prove of assistance in figuring out ways and means of locating cases of electrical trouble that seem to be somewhat out of the usual run.

One of the most common and often at the same time the most difficult electrical tests that has to be made is for the location of a fault in a conductor. Such faults may for our present purposes conveniently be divided into two classes, the first being grounds and short circuits, and the second complete breaks or open circuits.

LOCATION OF CROSSES AND GROUNDS.

If the fault in a grounded or crossed conductor were always of practically infinitely low resistance — that is to say, if it were a "dead" ground or short circuit — its location could easily be detected by measuring the resistance from the point of test and back again through the ground or through the other conductor affected, by any of the Wheatstone bridge methods described in the chapter on resistance measurements. Unfortunately, however, it is seldom the case that this condition exists, and tests giving results that are independent of the resistance of the return circuits and at the point of trouble are therefore necessary. Another very frequent source of inconvenience and error lies in the fact that at the fault there may exist an E.M.F. due in some instances to the contact potential difference between the faulty conductor and that on which it is grounded, or more commonly, with ground return circuits such as telegraph lines, to foreign earth currents.

In the majority of cases it is possible to obtain electrical access to both ends of the faulty conductor. If this is a cable coiled up in a tank we have the simplest case, as the two ends will, of course, be close together and may be carried direct to the measuring apparatus. Where the fault is on a line wire or cable it is almost invariably the case that another parallel conductor that is not faulty is available, and if this is connected to the faulty one at the distant station a loop is formed whose terminals are adjacent in the testing station.

Tests which require that access be had to both terminals of a conductor so formed are called "loop tests," the most prominent ones being the following: —

The Murray Loop Test.

Referring to Fig. 229, B, P, E is the looped conductor, B, P being the outgoing wire having a fault at f, and P, E the return wire joined to the former at the distant station P. This loop is used to form one side of a Wheatstone bridge, the two other arms of the bridge, b and d, being formed by adjustable resistances such as those in an ordinary post-office pattern testing set. The galvanometer G and battery S are attached as shown, suitable keys K^1 and K^2 being inserted in the respective circuits. Then, as is the case in the ordinary Wheatstone bridge, a resistance in the battery circuit introduces no error in the result, requiring only increased battery power to get the same sensibility. This resistance in the Murray test is that offered by the earth between the battery terminals and the fault plus that of the fault itself. In making measurements, the resistances in b and d are first made equal and the galvanometer key K^2 then closed, whereupon, if an earth current is present the galvanometer will deflect a certain amount, which should be noted. The ratio of the resistance b to d is then altered until an adjustment is reached such that the galvanometer shows the same deflection, whether K^2 is alone depressed, or both K^1 and K^2 are depressed. If the resistance of the circuit B, P, E, which we will call L, is known, we then have from the law governing the Wheatstone bridge, $x = \frac{Lb}{b+d}$. The resistance of B, P, E is measured by a Wheatstone bridge in the ordinary way.

It is advisable to have the key K^1 of a special reversing type, so that when one of its buttons is depressed, current is sent through the circuit A, S, earth, F, in one direction, and when the other is depressed, in the reverse direction. This will sometimes give slightly different results for the two connections, in which event it is usually safe to assume that their mean is the correct value. If the results differ widely, the contacts should be examined and cleaned, and the apparatus should be more carefully insulated from the ground. The test should then be repeated until concordant results are obtained.

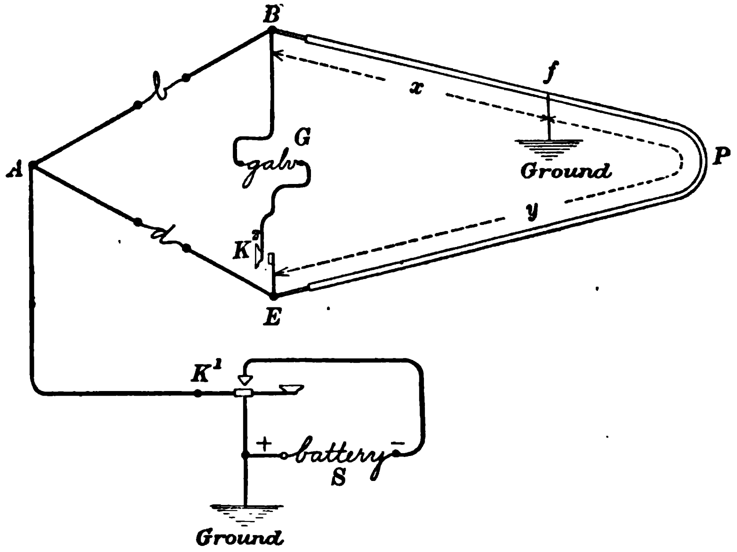

FIG. 229.

Ohmmeter Test.

In the Murray loop, as in all other Wheatstone bridge tests, the position of the galvanometer and battery in the network of conductors may be interchanged without affecting the results.

The ohmmeter mentioned on page 107 may be used for this modification of the Murray test by making connections as shown in Fig. 230. As will be seen from this, the standard resistance coil forming one arm of a Wheatstone bridge in the apparatus is cut out of use by withdrawing the connecting plug and allowing it to hang free. The middle post is connected to ground, and the ends of the looped line wire are attached to the two outer posts. The stylus is tapped along the wires forming the ratio arms of the bridge, as in finding a resistance, until a point of silence is reached, which point is of course an image of the point of trouble on the line. The latter can then be located by reference to the equally divided scales that come with the apparatus, and which show the result in percentage of the total line length included between the two posts.

The result so found is, however, correct only when there is no difference of potential between the grounded wire and the grounded post on the ohmmeter, as if such exists, due to earth currents or otherwise, the point of silence on the bridge wire is not the image of the fault, but a false one corresponding to the false result that would be obtained if, in the Murray method above, actual galvanometer zero were used instead of the false zero obtained on depressing the key K^1 alone. The human ear is unable to identify, with even the roughest accuracy, the loudness of the click emitted by the telephone receiver, and therefore if the ohmmeter is to be successfully used for such fault location work, it must be provided with a galvanometer which can be switched in place of the telephone when making such readings, and the work done from a false zero, as in the ordinary Murray method.

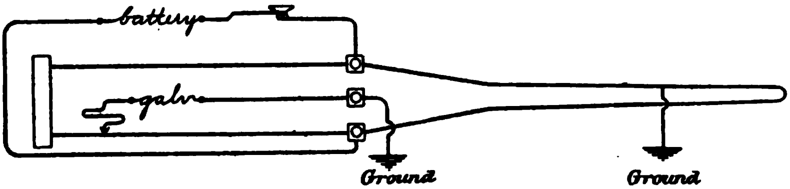

FIG. 230.

The Varley Loop Test.

In this, as in the Murray test, the two ends of the faulty cable must be made accessible by forming a loop with it and a good return conductor. The connections are then to be made as shown in Fig. 231, from which it will be seen that while the bridge arms, the galvanometer, and the battery are arranged as in the Murray test, a resistance, d, has been inserted between A and E. The arms a and b, of constant value in this test, are usually made equal to one another, and d is adjustable and varied until the galvanometer shows the same deflection whether its key K^2 alone is closed or both it and K^1 are down at the same time. Under these circumstances $x = \frac{bL - ad}{b + a}$. In the case assumed above, *i.e.*, when $b = a$, this expression becomes $x = \frac{L - d}{2}$.

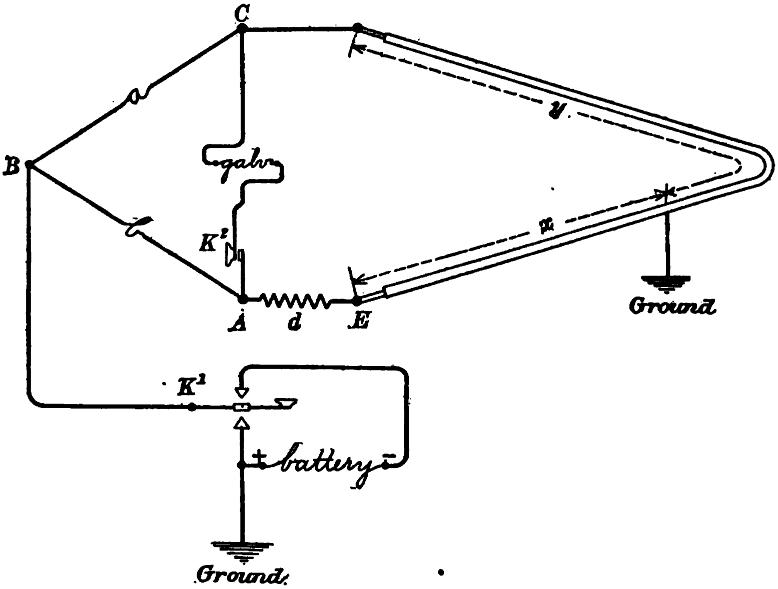

FIG. 231.

In order to have this test work at all it is necessary that the fault should be on the wire that is connected to the variable resistance d, because if it is not no balance can be obtained.

In connection with the Murray and Varley loop tests described above, the distinction between earth currents and those due to E.M.F.'s set up at the fault should be carefully borne in mind. Earth currents are possible only on lines a part of whose circuit is formed through the earth, as is the case of most telegraph and a few telephone installations. Contact E.M.F.'s at the break are, on the other hand, present both in ground return lines and in metallic circuits. As will be noted by careful reference to Figs. 229 and 231, a deflection of the galvanometer will be given when its key is closed and that of the battery circuit left open only when an earth current exists, and it is therefore correct to use the false zero as a balancing point only with grounded circuits. Where earth currents are absent, false zeros should not be used at all, and if there is a galvanometer deflection when the galvanometer key is closed and the battery key left open, it shows simply that there is leakage from the instrument and battery itself to ground. If this state of affairs exists, the leakage should be stopped by carefully cleaning all dirt and moisture from the insulating surfaces, and if necessary, by interposing additional resistances in the shape of porcelain insulators.

With all loop tests the accuracy is greatest with a high-resistance conductor. While telegraph and telephone lines have enough resistance to enable faults to be located with a sufficient degree of accuracy, such is unfortunately not the case with the heavy wires used in electric light plants. The errors are so large as to make the results perfectly useless, and recourse must therefore be had to other methods.

Induction Method.

This is one that, generally speaking, is possible with alternating-current circuits only. It consists in winding up of many turns of wire a coil that is made as large as possible consistent with portability, and is carried along by a couple of assistants over the faulty conductor with one of its flat sides parallel thereto. A telephone receiver is placed in the circuit of this "exploring coil," and as long as alternating current is flowing through the conductor, the current induced in the exploring winding will of course produce a loud humming noise in the receiver. Referring to Fig. 232, if the fault *f* is at *B*, the observer listening to the receiver when the exploring coil *E* is being carried along parallel to *A*, *C*, will hear a note until *E* has passed *B*. The terminal of the alternator supplying current to the good conductor must of course be grounded at the generating station in order that current may flow back through the ground at the fault.

This test is beautifully simple, but unfortunately not always applicable, especially under the conditions where buried alternating mains are most likely to be used, that is, in densely populated cities, as here numerous gas and other metallic pipes are usually present and the conductor may itself be inclosed in a lead sheathing, all of which so modifies the tone in the receiver that instead of there being an almost abrupt point of silence when the fault is reached, the noise simply decreases slightly, and it is very difficult to say just where this occurs.

Compass Test.

This simple and remarkably efficient test described by Mr. Stott in 1901 is available for the location of grounds not only in circuits which can be isolated while the measurement is being made, but, in the case of alternating-current systems, where the conductor is in use as well. It consists in sending through the faulty wire, the fault on it and back through the ground to the testing station a direct current of the highest convenient value. The direction of this continuous current is reversed at known and approximately equal intervals of, say, ten seconds, by means of a commutator that is driven either manually or by a small motor. Referring to Fig. 233, if the lower of the two conductors is grounded as shown, and if a periodically reversed direct current is being passed through the conductor, the ground, and back to the test station by the aid of the reversing commutator indicated in the figure, the needle of a pocket compass C placed parallel to the faulty main, will be deflected to a position nearly at right angles to the wire in one direction

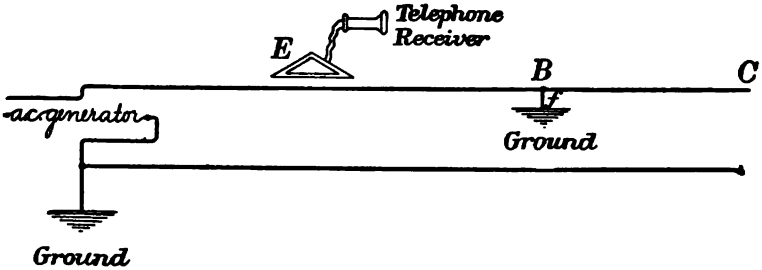

FIG. 232.

until the continuous current is reversed, at which time it will jump and take up a position removed nearly 180 degrees from the first one. If the wire under test is an underground conductor, the compass needle can be laid on its covering at each successive manhole until one is found where these periodical reversals of deflection no longer exist. The ground is then of course between the last point where the deflections were given and this one, and if the cable is tapped at the former, the point of trouble will usually be found there. In any event it has been located between two manholes, which is all that is usually required in practice, as if it exists in the intervening conductor, the cable must be pulled out of the ducts anyway in order to effect its desired repair.

The alternating current flowing through the main *B* does not affect the compass needle appreciably, as the rate at which the alternations take place is so much greater than the period of oscillation of the needle, that the latter either does not move at all or else simply trembles slightly, and has a motion which is negligible as compared with that due to the passage of the continuous test current. It is evidently impossible to make the same test with direct current in the mains *A*, *B*, as this causes a continued deflection of the needle in one direction, irrespective of any attempt to superimpose on it a reversed current. It is however possible in this case to substitute an exploring coil and telephone receiver for the compass needle and an alternating-current generator for the direct-current source with its reversing commutator *R*, but the current delivered by the *d c* machine must be sufficiently smooth to avoid producing a confusing noise in the telephone receiver. The current delivered by a Thomson-Houston arc machine is an example of one that pulsates sufficiently to make this exploring coil test out of the question.

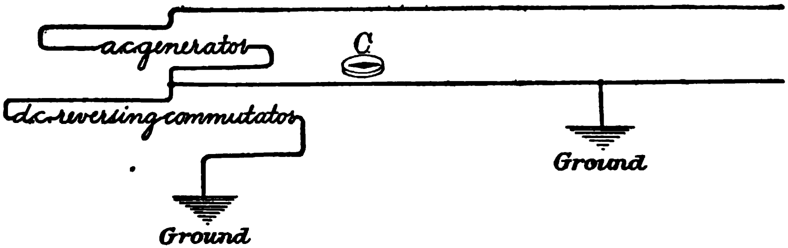

FIG. 233.

Fall of Potential Methods.

An elegant method of locating a ground in a faulty conductor is diagrammatically illustrated in Fig. 234. In this the faulty conductor is the line *B*, *D*; *A*, *B* being a length of good conductor connected in series with and preferably located parallel to *B*, *D*. A source of current *S*, usually a set of storage batteries, is used to cause a current to flow through the circuit, *A*, *B*, *f*, *G*, *G* as shown, and an ammeter *C* is inserted in that circuit so that it may be determined that the current strength is kept absolutely constant. If now we know the resistance of *A*, *B*, and take the drop in potential measured by a galvanometer or millivoltmeter across *A*, *B*, and *B*, *D*, respectively, the resistance of the faulty cable from *B* to *f* will be to the resistance of the good cable from *A* to *B*, as the deflection due to the potential drop between *B*, *D*, is to the deflection given when the instrument terminals are connected to *A*, *D*. In order that the resistance of the galvanometer leads may not introduce an error, it is necessary to use either a galvanometer whose resistance is extremely high as compared with that of *R* and *X* in the figure, or else, which amounts to the same thing, to have it of such high sensibility that a large resistance may be inserted in its circuit. If a section of conductor running parallel to *B*, *D*, cannot be used as *R*, a low resistance can of course be used in its place, but this plan is not as good, as the temperature of the stretch *X* is unknown, and if it differs greatly from the assumed 70° Fahr., on which its resistance measurement is based, an error equal to that of the temperature coefficient of copper, that is, two tenths of a per cent per degree Fahr., will be introduced. As the resistance at the fault *f* is often variable, it is most con-

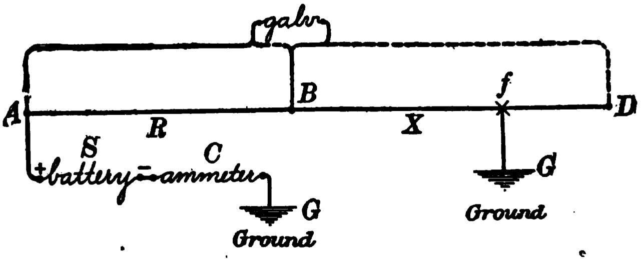

FIG. 234.

venient to use two galvanometers connected to the points *A*, *B*, and *B*, *D*, respectively, both graduated in known fractions of a volt, and then observe their deflections simultaneously. If this cannot be done, a single instrument and a switch for shifting the connections rapidly should be used, a careful watch being kept on the ammeter to be sure that the current has not changed, as on its having the same value during both readings depends the accuracy of the result.

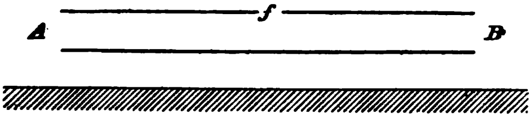

Fig. 235.

Location of Crosses.

Crosses are simply the grounding of one conductor on another, and may be located in exactly the same way that grounds are located, as described above, if the wire with which the cross has been made is substituted for the earth circuit in the ground tests. The localization of crosses is usually a more simple test than with grounded circuits, as the question of earth currents is entirely eliminated, and E.M.F.'s at the point of contact are of less common occurrence.

Location of Breaks.

Where a conductor is actually broken, and the return circuit from the break is therefore of a resistance that is practically infinitely high, we are confronted with a new set of conditions.

Whether the conductor is an aerial one or whether it is a cable buried in the earth or submerged in water, it may be considered as one coating of a condenser, the dielectric being the insulation from the point of test to the break, and the other coating being the earth or the surrounding water, as the case may be. The capacity of the condenser so formed may be measured by any of the methods of capacity measurement mentioned in Chapter VIII, and if this capacity is compared with that of a neighboring good conductor whose length to the distant station *B*, Fig. 235, is known, the location of the fault *f* is given directly by the ratio of the capacities. Where no apparatus capable of measuring capacity in microfarads is available the fault may still be located by simple comparison of the capacity of *A*, *f* with that of the good conductor *A*, *B*. The already much described ohmmeter can be used for this test to advantage, the connections being as in Fig. 236. In this test it is necessary that the potential applied to the bridge wire terminals be an alternating one which may conveniently be obtained from the secondary of an induction coil. The point of silence on the bridge wire is then one which divides up the total bridge wire length into two sections which are to each other as the capacities of the broken and good conductors.

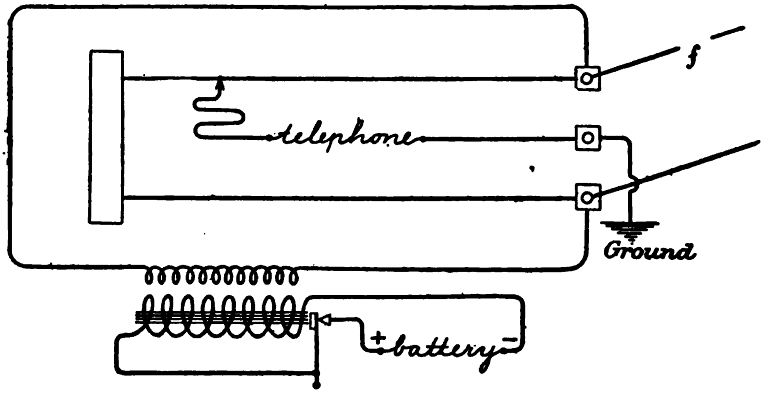

FIG. 236.

This ohmmeter test can be used only under favorable conditions, as the resistance of the slide wire is but small, and while it is without capacity has a small self-induction due to the fact that the wire forms a loop. A device for the location of breaks that

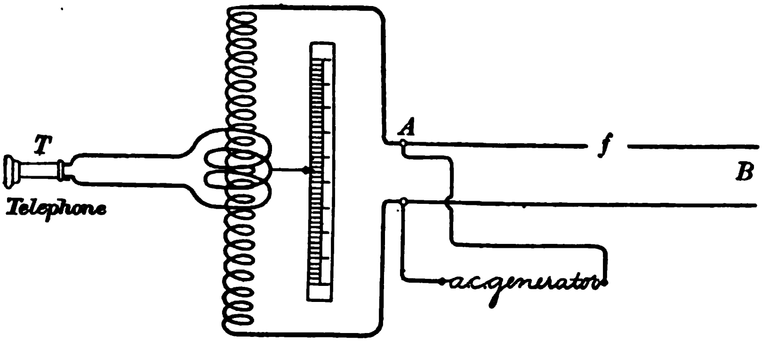

FIG. 237.

depends on a somewhat different principle and which is applicable to a greater variety of cases is the Meyers break finder illustrated diagrammatically in Fig. 237 and in perspective in Fig. 238. In this the secondary of an induction coil wound as a long spool has its terminals attached to the ends of the faulty and good wires respectively, and a narrow primary coil winding is arranged to slide up and down along the secondary.

Simple inspection of the figure will show that the primary may be moved to a position such that a telephone receiver connected across the secondary terminals will cease to emit a hum, and that if an index attached to the primary moves over a scale, the scale may be divided so that the ratio of the capacity of the good to the broken conductor and hence the ratio of the length of the good conductor to that of the faulty one up to the break will be shown directly.

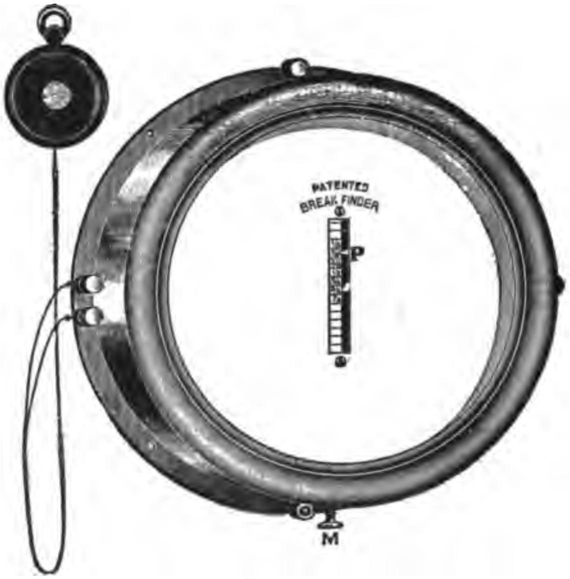

FIG. 238.

ARMATURE TESTING.

One of the most common tests that has to be made under commercial conditions is the location of a fault in the armature of a generator or motor. The extent and nature of the discoloration of the commutator bars will sometimes give an indication of the nature of the difficulty if the machine has been in operation, but the trouble may be more surely located by calling in the aid of measuring apparatus.

Electrical faults in the windings of an armature consist either of a ground between the winding and the iron core, or of a wholly or partially short-circuited section, or of a section that is of high resistance or all-together opened.

Testing for Grounds.

The fact that a ground exists in an armature is easily determined in a dozen different ways, one of the simplest being to pass current from an outside source through an incandescent lamp in series with which there is placed the suspected armature, one wire being attached to the shaft and the other to the commutator bars. If the lamp lights, there is of course electrical contact between the windings and the shaft. If this or any other method shows that a ground exists, it may be located as follows: Referring to Fig. 239, current is passed from the

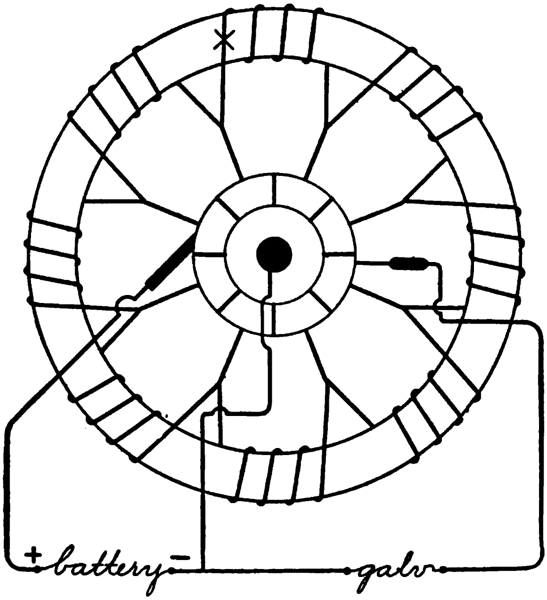

FIG. 239.

shaft through the ground and back to the commutator by means of conductors attached to one brush and to the shaft respectively. The current may be taken from a convenient electric-light main, an incandescent lamp being interposed to prevent an excessive flow. A galvanometer, which in central stations may conveniently be a switchboard ammeter of the shunt type with its shunt disconnected, is then attached so that one terminal is on the shaft and the other free to be moved around the commutator. If the ground is at that point of the winding designated by the cross in the figure, the deflection of the galvanometer will be a minimum when its terminals rest on the commutator bar to which that lead is attached. If the ground were midway between the terminals attached to two adjacent commutator bars, the deflection at these two bars would be alike and both would be less than that given at any other point on the commutator. All that is usually desired is to know which coil the ground is in, but this feature enables one to tell approximately at what point on the length of the coil the ground is located as well by observing the magnitude of the deflection given when the galvanometer terminal is on the two adjoining commutator bars.

Location of Crosses.

Current is passed through the armature under test through two of its sets of brushes, these two being usually selected so as to be diametrically opposite. The current is taken from another main, as in the preceding test. Terminals from a galvanometer, which may likewise be a shunt type ammeter without its shunt, are then placed on adjacent commutator bars, as shown in Fig. 240, and the deflection noted. This operation is repeated around the whole circumference of the commutator, bar by bar, and the deflections will all be alike (if the strength of the current flowing through the armature is kept constant), until the bars to which the ends of the defective coil are attached are reached, whereupon the deflection will naturally be less as the current, instead of being obliged to flow through the full length of the coil, then shunts part of it through the short circuit. This is usually called the "bar to bar test."

In making the above test, it must be borne in mind that any decrease in the strength of the current through the armature means a decrease in drop between adjacent bars. When testing on a fairly steady circuit, it is usually sufficient to place an ammeter in the supply line and see that the current does not change too greatly.

When the current is taken from a source like a street railway line, however, where the E.M.F. is constantly varying over a wide range, it is better to use either two separate millivoltmeters or a combination one like that mentioned on page 129. By using a separate armature coil known to be perfect, or even a length of the wire leads to the armature of equivalent resistance, as a shunt to one instrument, the other instrument will give the same reading when its terminals are touched to the adjacent segments of a good coil and a lesser one for a short-circuited coil. The deflections may vary at different times, but as long as they are alike the coil under test is known to be good.

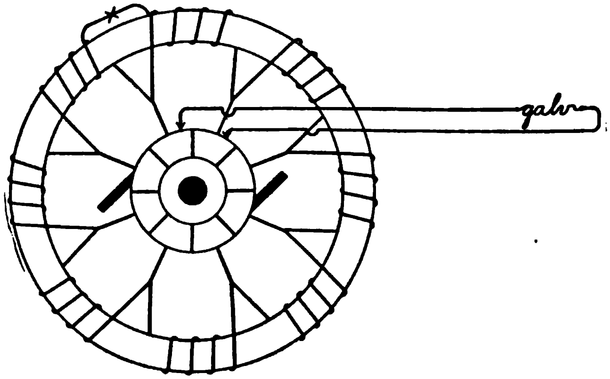

FIG. 240.

Location of Open Circuits.

For locating open-circuited coils connections are made exactly as shown in Fig. 240, but the strength of the current passed through the armature is decreased or the galvanometer sensibility made less by inserting a resistance in series with it or a shunt across its terminals. No deflection will be given as the galvanometer terminals are carried from each adjacent commutator bar pair to the next until those two are reached between which the open circuit exists. At this point there will be an electromotive force equal to the total drop between the two brushes, and the galvanometer needle will be violently deflected.

Location of Reversed Coils.

A coil whose connection to the commutator bars is the reverse of the proper one is a rare occurrence, but it sometimes happens that in winding an armature this mistake is made. If the armature is tested by the bar to bar method above described, a reversed coil is detected at once when the galvanometer terminals are applied, as the needle will swing in a direction opposite to that which it took with all the other and properly connected coils.

Coil Resistances.

If the strength of the current that is being passed through an armature is known by inserting an ammeter in that circuit, and if the galvanometer is calibrated in millivolts, the bar to bar test will give the actual coil resistance in ohms by simple calculation, using Ohm's law. In making such calculations the armature connections must be borne in mind, as the current through a good armature flows always through two and often through more branches of equal resistance connected in parallel, so that the current shown by the ammeter must be accordingly reckoned per coil.

PART II.

CHAPTER I.

RECORDING INSTRUMENTS.

The phrase "recording instruments" is often used to designate an integrating instrument whose indications show the product of the average current or wattage by time, but the term is incorrect in this sense, as it actually has reference to an instrument in which some marking device inscribes on a record chart a line showing the instantaneous values of voltage, potential, current, or power, at all times. Such recording instruments are also called registering instruments.

The principle on which such devices are based permits of dividing them into three general classes: the first is that in which an ordinary indicating instrument of any of the types heretofore described has attached to its needle a marking pen or pencil which moves over a chart that is being continuously pulled forward by clockwork; the second class takes in those recorders in which there is likewise used an indicating instrument mechanism, but whose needle is free to move and take up any desired position, a device being attached through whose aid the needle positions are marked on a clockwork-driven chart at regular intervals; the third class of recorders might be termed "relay recorders," in which the mechanism of an indicating instrument actuates a marking device, not directly, but through relays which control some source of mechanical power of relatively great strength.

RECORDERS OF THE FIRST CLASS.

Bristol Recorders.

The simplest of the recorders of the first class made in this country is the Bristol instrument illustrated in Fig. 241. In it the chart takes the form of a paper disk, which is rotated by clockwork at an appropriate rate. The instrument mechanism consists of a solenoid voltmeter or ammeter whose main winding is a coil whose axis is placed horizontally, and whose core actuates the upper end of the needle shown, the force opposing the motion of the needle being the elasticity of its lower flat spring end. The upper end of the needle carries a V-shaped trough in which there is placed a drop or two of slow-drying glycerine aniline ink which is drawn to the end of the trough by capillary attraction and so makes a fine line on the paper.

Aside from the fact that the charts on such instruments are unsatisfactory because the abscissa and ordinates are not straight lines crossing at right angles, but circle arcs, so that the records are difficult to interpret and practically impossible to integrate with a planimeter, the friction between the pen and the paper is so great as compared with the power exerted by the instrument mechanism that a considerable change in load must take place before the pen will move, and even then it may take up a position which does not accurately indicate the new value. The error due to this friction may easily be in excess of 5 per cent.

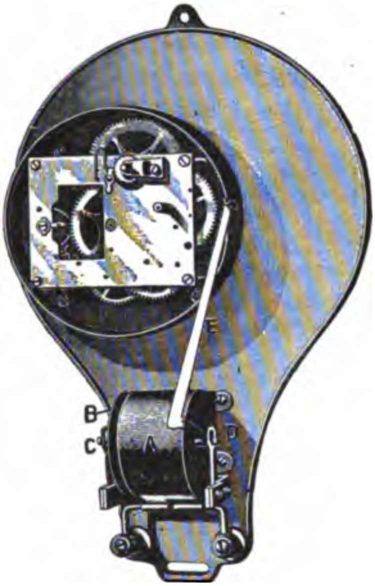

FIG. 241.

Chauvin and Arnoux Recorders.

An ingenious device for partially eliminating the above-mentioned friction errors is used on the recording instrument made by Chauvin and Arnoux, of Paris. This consists of an ink roller which is attached to the end of a needle actuated by an enlarged specimen of an ordinary indicating instrument movement, the roller being shown in Fig. 242. It consists of two halves, *A* and *B*, the former of which is open above and below and the latter above only. A lenticular piece of porous porcelain or a disk of blotting paper is placed between *A* and *B* and the two then screwed together by an appropriate thread, so that only a very fine gap is left between them. Both the upper end of *A* and the lower end of *B* are provided with small jeweled bearings which in turn rest on pivots, both of the pivots being secured to the pen frame, *F*. This leaves the roller free to rotate about its axis. A drop of alcohol is first allowed to fall into the open end of *A*, and this moistens the porous washer and tends to flow outward through the crevice between *A* and *B*. Aniline ink is put into *A* immediately after, and this follows the course of the alcohol, so that the ink is drawn to the edge and will of course make a mark on the paper chart rotated at right angles to and in contact with it. A complete Chauvin and Arnoux recorder having an actuating mechanism of the hot wire indicating instrument pattern is shown in Fig. 243, which cut will make the method of attaching the pen more clear.

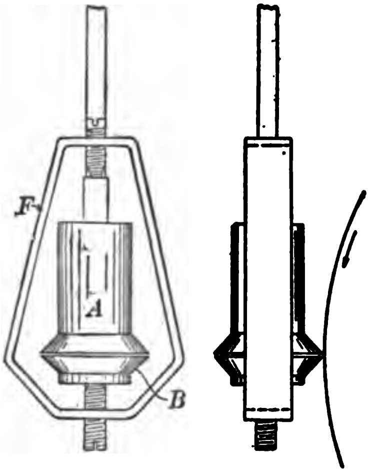

FIG. 242.

This rolling pen reduces the friction between the marking device and the chart very materially, but it makes rather a broad line, so that it is difficult to detect minute changes by inspection of the record curve.

General Electric Co. Recorder.

Strictly speaking, this also is a recorder in which the records are obtained by attaching to the extremity of the needle of an indicating pattern instrument a pen, which by its travels over the surface of a paper chart carried beneath it by means of clockwork, traces a curve showing the variations in current strength. The problem of eliminating the frictional errors due to the friction of the pen on the record sheet has in this device been attacked by an endeavor to make the torque of the moving system so high that the frictional retarding forces form but an inappreciable percentage thereof. One of the expedients involved is the reduction of the angular motion of the needle to about 20° in place of the conventional 80° or 90°. This of itself brings about a quadrupling of the effort exerted for a given percentage change in load, although it involves, too, chart ordinates which are very short. A still further increase in the power for actuating the recording pen is obtained as follows: The measuring instrument portion of the apparatus is that of the conventional d'Arsonval meter kinematically inverted, that is to say, the moving coil carries a steady current of the maximum strength permitted by the design and swings in a magnetic field whose intensity varies with the load to be measured, in place of having the coil current the variable and the field strength fixed at the maximum that the design allows.

There is thus a moving coil whose windings carry a constant, uniform current from some separate source and stationary coils furnishing the field in which the movable one swings. The plan necessitates the complication of a set of storage batteries to supply the moving coil current and an indicating instrument in that battery line to show that the current strength remains unchanged, but has the advantage that the current from the source to be measured may be of almost any value as it flows through stationary windings, and there are hence no difficulties because of the limited current capacity of springs or the like. Excellent damping qualities result also, owing to the intensity of the field in which the coil swings.

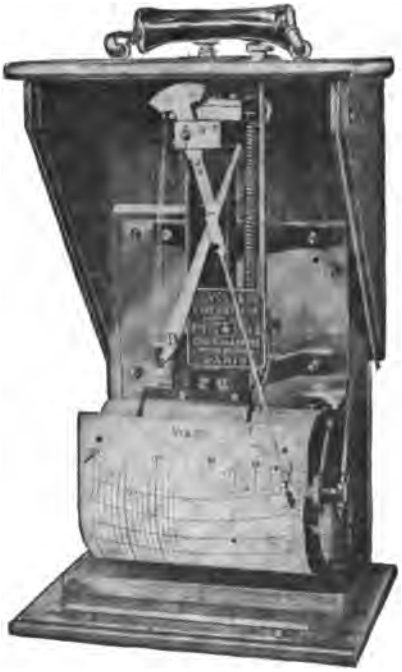

FIG. 243.

A General Electric recording ammeter is shown in Fig. 244, where the indicating instrument relied upon to show that the strength of the current through the movable coil windings remains unchanged, is likewise visible. The same clockwork that draws the band of paper along under the marking pen makes marks on the chart at regular time intervals, from which marks the elapsed time may thus be read off.

While heavy, cumbersome, and costly, the apparatus forms probably the best means available to-day for obtaining continuous records of rapidly fluctuating loads within its capacity, being specially valuable for such work as the plotting of the current input curves of elevator and street railway motors.

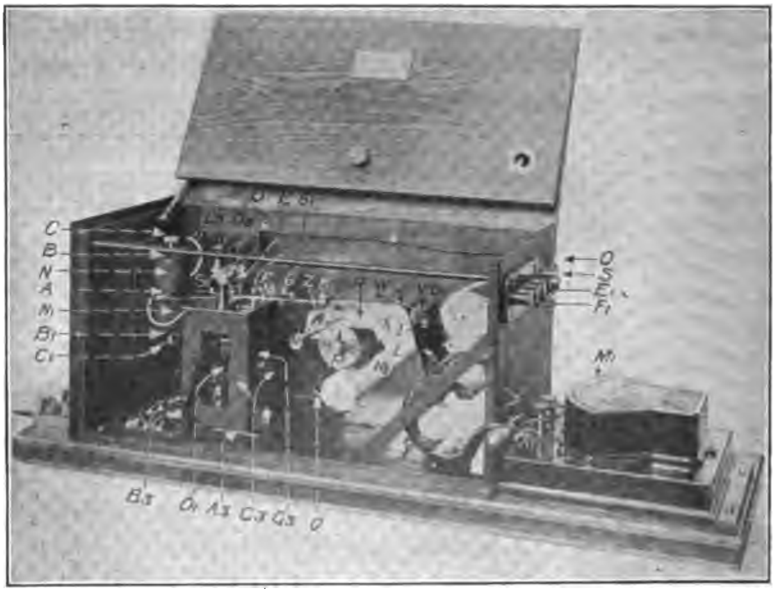

FIG. 244.

RECORDERS OF THE SECOND CLASS.

Gans and Goldschmidt Instrument.

In this device the clockwork and paper drum arrangement is much the same as in the Chauvin and Arnoux recorders, but the pen carried by the indicating instrument is not kept in constant contact with the paper. As can be seen from Fig. 245, a curved arm extends across the scale and above the needle. This arm is sharply knocked down toward the paper at regular intervals, controlled by a clock, and as this happens, the marker attached to the indicating needle is likewise hammered against the paper, so that registry of a number of individual indications is made and conveys practically the same information as if the record of the meter were a continuous one.

This type of instrument is attractive on account of the fact that the mechanism actuated by the current may be of the conventional indicating instrument power and design, for, being entirely unhampered in its motion, except at the instants when it is struck by the striker bar, the needle swings as freely as that of an indicating device. The periodic arresting of needle motion is, if anything, rather an advantage in so far as these checks serve to prevent the needle of otherwise poorly damped apparatus from swinging about too violently. The apparatus is not satisfactory on a rapidly fluctuating load, as the striker bar does not work with a rapidity sufficient to cause the successive dots on the chart to follow one another closely enough to give an approximation to a continuous line under the circumstances.

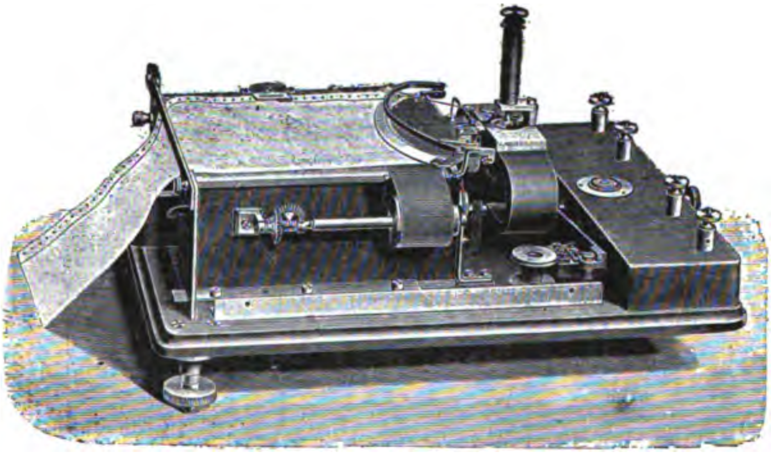

FIG. 245.

No meters of the type are made in this country, but they are in limited use abroad, particularly for recording the deflection of instruments with low torques like galvanometers.

RECORDERS OF THE THIRD CLASS.

The Callendar Recorder.

One of the earliest relay recorders is the Callendar instrument, which is primarily a recording slide-wire bridge. Fig. 246 shows its method of operation. In that figure *MN* is the straight stretched wire of an ordinary slide-wire bridge, the standard and unknown resistances being inserted in the usual way, as likewise are the battery and galvanometer circuits. The sliding contact on *S* slides along a bar, and is pulled toward *M* or *N*, as the case may be, by the endless cord shown passing over the idle pulleys, *DD*, and making a turn around the drum, *P*. The galvanometer is special, in that when it deflects because the bridge circuits are unbalanced its needle comes against one of the other of the stops *E* and *F*. When it is against *E*, a circuit which can be traced out from the figure is closed, and this energizes an electromagnet, *I*. This magnet pulls down one end of a lever, and in so doing raises the other end, which is a brake that prevents the gear wheel, *R*, from turning. As *R* then rotates, it in turn actuates the pinion, *B*, which latter rotates the drum, *P*, and pulls the sliding contact in the direction that it must be moved in order to restore the balance. If the galvanometer needle touched *F* instead, the pinion, *A*, would be actuated, and the drum, *P*, would pull the sliding contact in the opposite direction. The manner in which the drum, *P*, is caused to rotate in one direction or the other, according as *B* or *A* is turning, is best seen from Fig. 247, which shows an enlarged view of this mechanical appliance. *Q* is a stationary shaft on which

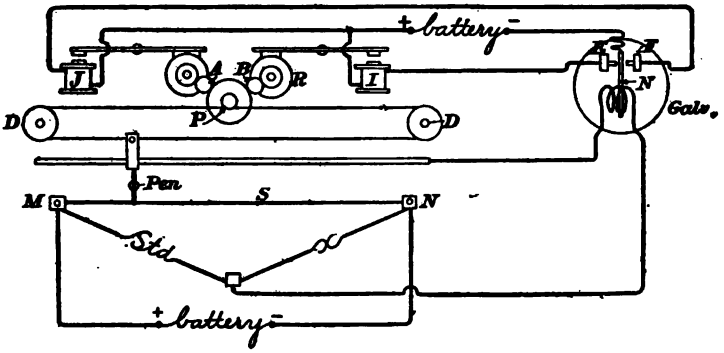

FIG. 246.

a gear wheel, *K*, may rotate freely. This wheel and its mate, *L*, are provided with both spur and bevel teeth. *L* is free to rotate on the outer surface of the shaft, *T*, carrying the drum, *P*. Fastened at right angles to *T* is an arm, *U*, on which there rotates the bevel pinion, *V*. If *A* and therefore *K* are stationary, and *B* rotates, *L* will evidently be revolved about *T* and in so doing will not only rotate *V* about its axis, *U*, but will carry *U* around the shaft, *Q*. In like manner, if *B* and hence *L* are stationary, and *A* rotates, *K* will rotate *U* about *Q* in the opposite direction. If both *A* and *B* were released from the control of their brakes simultaneously, as would practically be the case if the galvanometer were subjected to heavy mechanical vibration so that it tapped *E* and *F* in rapid succession, *V* would rotate about *U*, but *U* would not rotate *T* around *Q*. This device is like the balance gear used on automobiles.

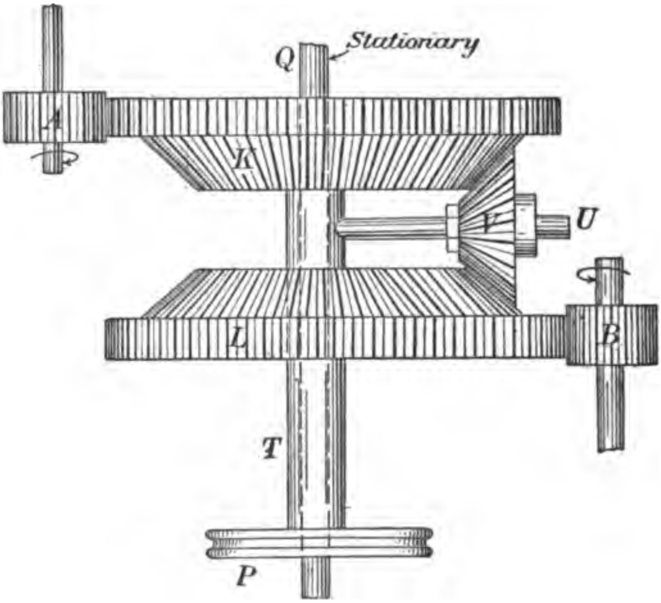

FIG. 247.

The power for driving *A* and *B* is obtained from a pair of independent clockworks. A pen carried by the arm that supports the sliding contact, on *S*, is drawn backward and forward on the record paper by it, and so makes the desired chart.

While the instrument as described is a recording bridge giving a record of any changes in the value of resistance, *X*, it can, as is evident from the chapter on slide-wire bridges, easily be modified to become a recording potentiometer, in which case it will give records of potentials, currents, temperatures, etc.

The Arconi Recorder.

In this device the needle of an indicating instrument actuates, as is shown in Fig. 248, a contact which comes against one or the other of the stops *A* and *B* when the value of the current flowing through the instrument changes. A motor, *M*, is set in rotation when the needle is in contact with either stop by completing the circuit through the motor armature, and revolves in

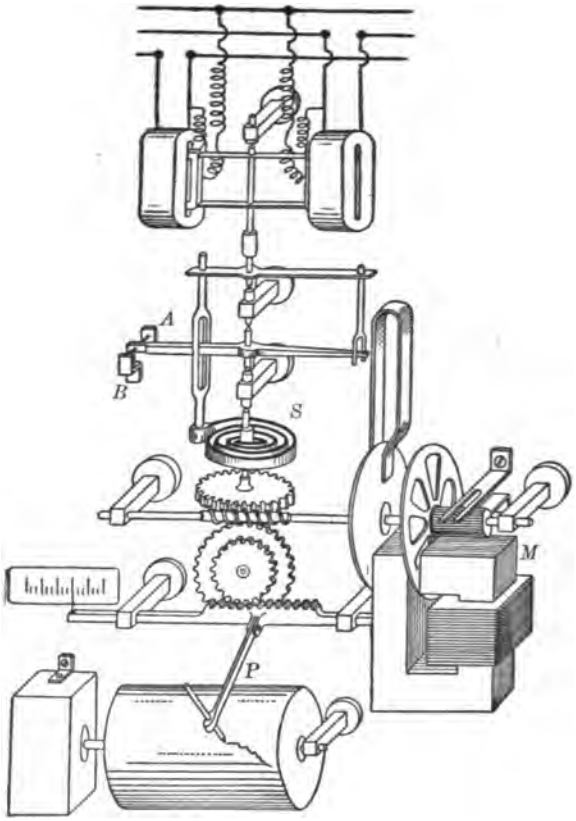

FIG. 248.

one direction with the contact on A, and in the reverse direction when it is on B. The torque exerted by the instrument needle is opposed by that of the coiled spring, S, and the free end of that spring is attached to a carriage that is driven by the motor.

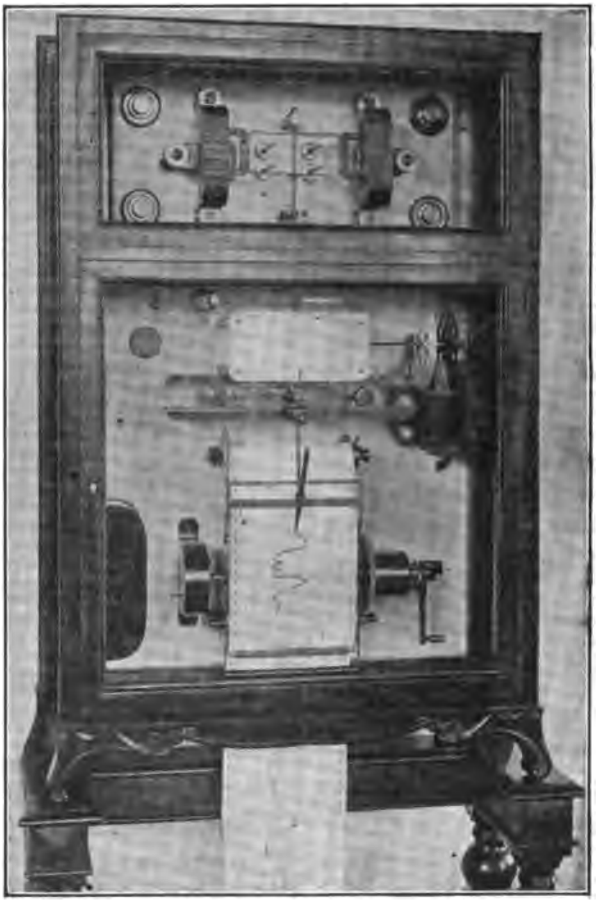

FIG. 249.

The connections are such that when the current strength increases the needle makes the contact for that circuit which will revolve the motor armature, and hence move the spring terminal in such a way as to increase the spring tension. The motor will of course be kept on rotating until this increased tension is sufficient to pull the needle away from its stop, whereupon the circuit is broken and the motor comes to rest. A pen, *P*, is attached to the rack that is moved by the motor and traces on the chart the varying positions that the rack has assumed and which show the measures of the current strength.

The indicating instrument mechanism may obviously be either a voltmeter, ammeter, or a wattmeter, according to the quantity that it is desired to observe.

A complete instrument of this kind is illustrated in Fig. 249.

The Weston Recorder.

This device is similar to the Arconi recorder, in that an indicating instrument mechanism causes the direction of rotation of an electric motor to reverse according as the needle deflects against one or the other of a pair of stops, and in that the pen that makes the record on the chart is moved back and forth by the motor. Instead, however, of varying the magnitude of the torque resisting the swing of the needle by the position of the recorder carriage, the torque actuating the needle is varied by varying a resistance placed in series with the indicating mechanism. A diagrammatic illustration of this device is shown in Fig. 250, and will be understood without further explanation.

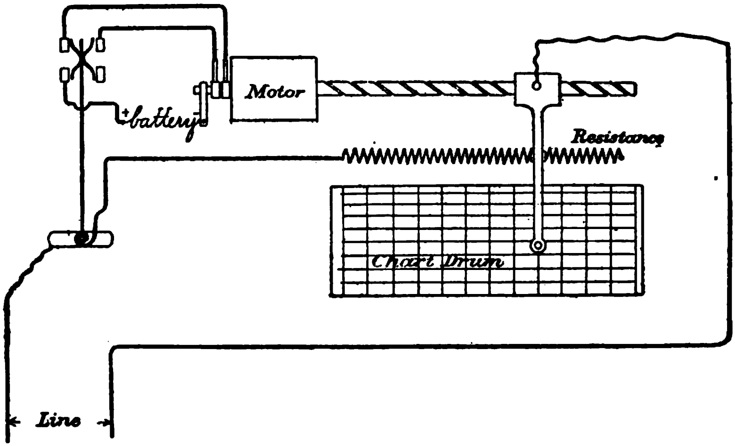

FIG. 250.

Another form of Weston recorder is that illustrated in Fig. 251. In this neither the torque of the indicating needle nor that of the spring opposing its motion is varied, but the position of the stop contacts is changed instead. As is shown by the figure, the stops are carried on a frame mounted co-axially with the indicating mechanism, and are caused to rotate by a motor which drives their frame through gears. The direction of the rotation of the motor is determined by the pair of stops with which the needle is in contact, and it carries the frame with the contacts along, until the circuit is broken and the needle left free. The recording pen is driven back and forth on its chart by the motor.

Boyle's Recorder.

This piece of apparatus is diagrammatically illustrated in Fig. 252. It employs an ordinary indicating instrument mechanism, *I*, on which there is a needle with a contact point at its end, as in the apparatus above. The stops against which this contact plays are, however, not stationary, but composed of two plates, *S* and *T*, insulated from one another but mechanically secured to a common framework and in rigid connection with a piston, *P*, moving in a cylinder. When the needle makes contact with one of the plates, say *S*, a circuit is closed through a local battery and *S*, and through two electrically controlled valves, E^1, E^2. When current flows through the valve windings both are opened. As will be seen from the figure, this with the piping arrangement shown will admit water that is supplied under pressure from ordinary service mains to the lower side of the piston, through the valve, E^2, while at the same time the opening of the valve, E^1, offers a free passage for the escape of the water from the upper and opposite side of the piston, *P*, to the atmosphere. The result of this unbalanced pressure on the

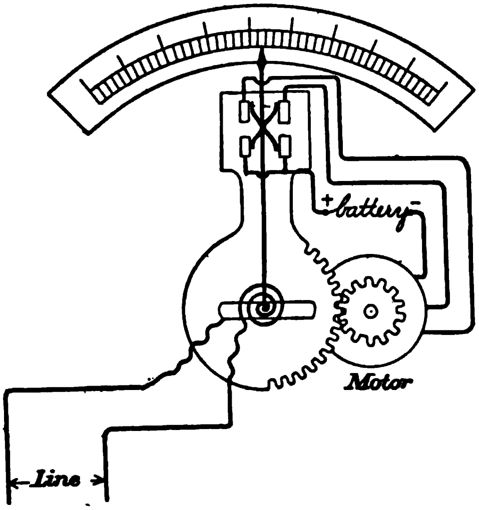

FIG. 251.

piston is to raise it, together with the contact plates, S and T, attached to the piston rod, so that the pointer of I is free to deflect further toward the left. As long as the torque of I, exerted by the current flowing through the mechanism, is less than the restraining force offered by the springs, I will remain in contact with S, but as S moves up a position will finally be attained where the forces acting on the needle are in equilibrium, and its extremity will therefore rest between the plates S and T, but not in contact with either.

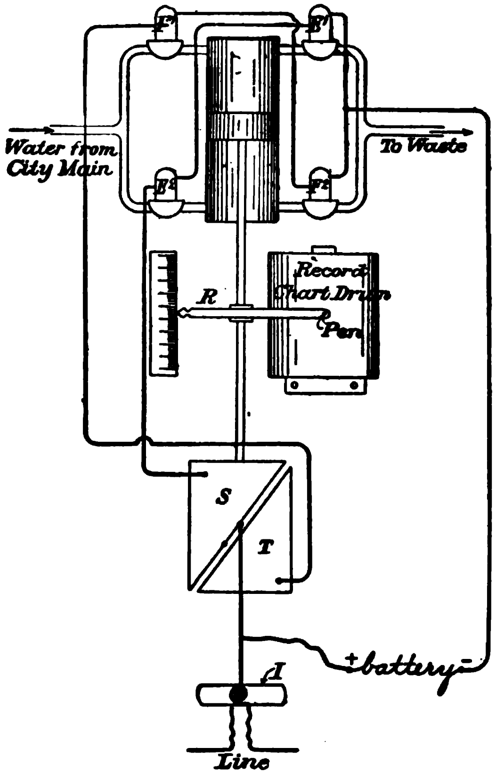

FIG. 252.

If an increasing load were applied to I, the pair of valves, F^1 and F^2, would be opened, and T and S would rise instead of fall. A pointer, R, is attached to the piston rod and moves over a scale which is divided so that the values of the current strengths may be read off directly. The same rod carries also an inking pen that rests in contact with the clockwork-driven record sheet.

A detail view of one of the electrically operated valves is shown in Fig. 253, which is practically self-explanatory. The upper part of this apparatus is held to the lower one by means of a clamp, so that if it is desired to have access to the valve at any time this can be done by the simple removal of a screw. A copper diaphragm is interposed between the windings of the electromagnet and the iron core on which it acts, in order that moisture may not enter and spoil the windings.

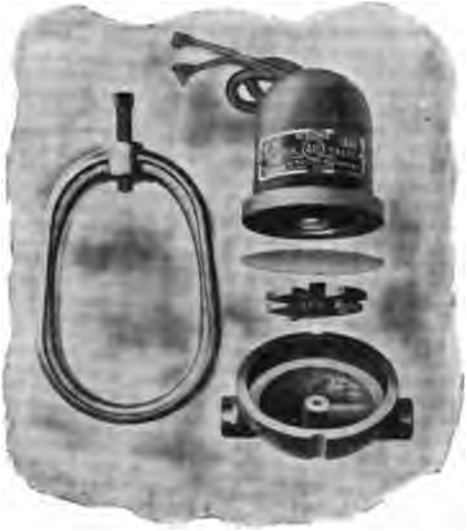

FIG. 253.

The possibility of varying the outline of the gap left between the plates *S* and *T* of the recorder forms an interesting feature of this apparatus. If the instrument whose fluctuations are to be recorded is of the equally divided scale type in which equal current increments give equal increase of angular displacement of the needle, the straight slot illustrated is employed, and the resultant record chart is one for which ordinary cross-section paper may be employed, like numbers of divisions of the ordinates indicating like amounts of current at all points between the horizontal reference line and the boundary full capacity line. This enables the mean height of the record curve to be determined by simple integration of its inclosed area with a planimeter and dividing this by the length of the chart, as in the case of steam engine indicator cards.

If the excursions of the pointer of the indicating instrument do not vary in direct proportion to the changes in current strength and the straight gap is used, the chart divisions would be like the scale divisions, *i.e.*, if the latter are crowded together at any part of the scale the chart abscissæ will be close together at the same part. By suitably curving the slot, however, it is possible to make an indicating instrument movement whose scale divisions are not of equal width give a chart with equal divisions by causing the excursions of the piston to vary in direct proportion to the current strength. With an alternating-current voltmeter having a scale of the character shown in Fig. 149 the slot required to enable the use of ordinary section paper as a chart would be shaped somewhat like that shown in Fig. 254. It will be seen that when the contact on the needle is at the point *A* a very slight swing of the needle is sufficient to close the circuit in one direction or another, that if the needle is near the point *B* it will make a larger angular swing before coming in contact with a plate, and that when it is at *C* the original status of affairs recurs, except that here the contact may move a little further, as the scale of the indicating instrument is more open at the highest point of its range than at its lowest.

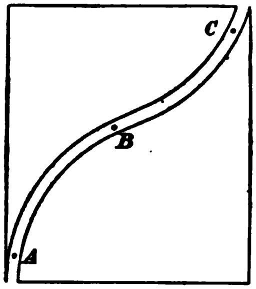

FIG. 254.

CONTACT TROUBLES.

In all of the relay recorders so far described, the mechanism of an ordinary indicating voltmeter, ammeter, wattmeter, or galvanometer is obliged to exert a sufficient torque to cause a metallic button carried by its needle to make an electrical contact with a stop.

Even with fresh, smooth surfaces the pressure that must be exerted to force them together firmly enough to obtain good electrical contact is appreciable, and as the contacts become somewhat roughened, due to the slight but constant sparking when the motor or clutch circuit is made and broken thereat, the pressure required becomes still higher.

The requirement of high contact pressure means low sensibility of the instrument as a whole, and its failure to record small fluctuations, as large current changes must take place before the contact carried by the movable element is pressed against its mate with the requisite force. Obviously a very small particle of dust lodging between the contacts will have the same effect.

This difficulty, while seemingly trivial, has proven to be the greatest drawback to relay instruments, and in fact is the principal reason why none of them are yet in extensive use although their inception dates back many years.

Various devices have been employed to minimize the trouble, the more prominent being the following:

Rubbing Contacts.

Fig. 255 shows the expedient devised by Professor Callendar for use in his recorder. As will be seen from this, the needle, *S*, of the galvanometer plays between two contacts which are made in the form of wheels that are being slowly rotated by a light thread belt driven by a clockwork mechanism. Each wheel is of brass, and into its periphery there is let a circle of platinum wire which projects above the wheel face. The tip of the galvanometer needle is of platinum also, so that when it deflects against either wheel edge, a contact is made between platinum and platinum, and one of the faces is kept rotating at right angles to the other, thereby not only continuously presenting a fresh surface, so that the heat developed at the point of contact

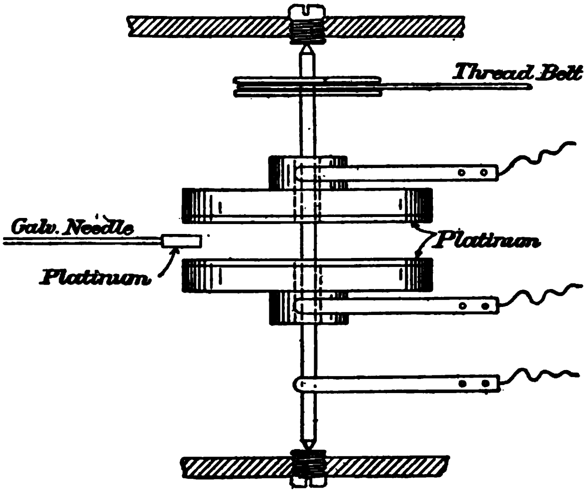

FIG. 255.

is less apt to prevent incipient fusing, but the rubbing polishes the surfaces and thus tends to keep them in good condition.

In the figure the contacts between the wheels and the brake circuits are shown as being made through springs pressing on the wheel hubs. This is often modified by supporting the axles on which the wheels turn in plain metallic bearings, the amount of current to be transmitted being sufficiently small to admit of this practice.

Relays.

Another method of overcoming the difficulty due to handling comparatively large currents through the contact made between the instrument needle and its stop is to use ordinary electric relays similar to those employed in telegraph practice, so that this circuit need carry only enough current to energize the relay, leaving the relay contacts to carry the heavy current that is necessary to work the clutches or the motor. By this expedient the current controlled by the instruments may be limited to one in which the sparking between the needle contact and its stops is inappreciable, or at all events not enough to roughen them with a consequent decrease in sensibility.

Such relays are, however, open to the objection that they involve the use of an additional battery circuit, and so add considerably to the complexity of the device and to the fact that they are expensive. Without them, on the other hand, it is exceedingly difficult, if not impossible, to make a recorder of the third class that will be free from contact troubles when used for extended periods.

WADDELL AND LEGRAND RECORDER.

These interesting instruments are based on a novel principle. Referring to Fig. 256 herewith, air under a pressure of approximately three pounds to the square inch is supplied through a pipe, *A*, to the instrument. This air is first obliged to pass through a long fine-bore passage, *B*, and then into a chamber, *C*, of relatively large volume. This chamber is supplied with an escape valve, *D*, which is similar to a safety valve, the load on whose disk, *E*, is determined by the strength of the current to be measured. As in the case of any vessel provided with a safety valve of comparatively very large capacity, the pressure in the vessel is determined solely by the blowing-off pressure to which the valve is loaded. Small variations in the pressure of the air supplied through *A* do not vitiate this result, as the effective area of the passage, *B*, is so much less than that through the valve, *D*, that the latter can take care of any of the fluctuations in the rate of supply to the chamber, *C*. The manner in which the valve disk, *E*, is loaded by varying currents is also shown in the figure. A coil, *F*, of insulated wire is arranged in the annular field supplied by the magnet, *SN*, with its extension pole piece, *s.s.* This coil is supported on one end of a lever, *G*, that is free to oscillate about the fulcrum, *H*, and is partially counterbalanced by the adjustable weight, *I*. When current flows through the spool the reaction between the magnetic field that it furnishes and that of the permanent magnet exerts a pressure on the valve that is in direct proportion to the current strength. The valve is therefore loaded in proportion to the current strength, and the pressure in the chamber, *C*, hence varies with the current. The recording device is formed by a float, *J*, that is carried up and down in the manometer, *K*, by the variation in pressure on its surface. A pen is carried on a rod that is rigidly secured to the float, and as it is moved up and down by the latter traces a line on the chart that is revolved before it by clockwork and shows the variations in current strength.

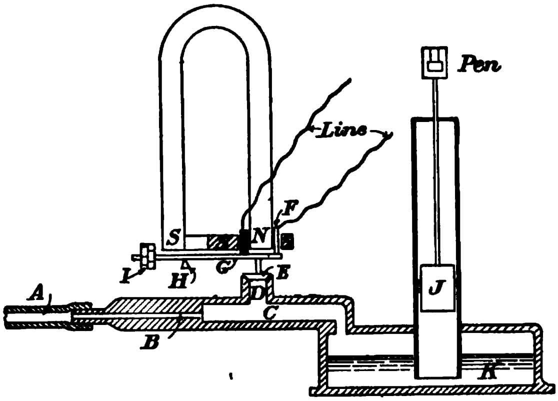

FIG. 256.

A complete instrument of this class is illustrated in Fig. 257.

As described, the apparatus is suitable only for the measurement of continuous currents, as only these will give the necessary reaction between the permanent magnet and the coil through which the current flows. Alternating currents are measured by substituting for the magnet and coil mechanism, any of the indicating instrument mechanisms that have been described on preceding pages and arranging them so that there is no restraining force, the needle instead pressing on the valve.

A modification of this kind is the recorder for measuring the total output of a multiphase circuit, this being shown in Fig. 258. Here the lever which loads the valve is double ended and carries at each extremity a spool through which there flows current of a strength proportional to the voltage. Each spool works in the field furnished by a solenoid through which passes the total current to be measured, and each end of the lever is hence a wattmeter. By making the electrical connections such that the right-hand end, *A*, of the spool is

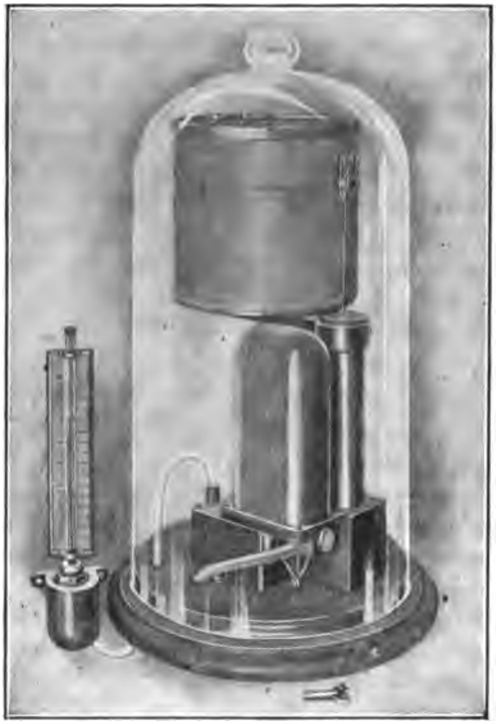

FIG. 257.

depressed and the left-hand end, *B*, raised when current flows through its windings, the load on the valve evidently is the sum of the efforts. As was pointed out on page 230 the output of a three-phase circuit is obtained by adding together the indications of two wattmeters having their series coils connected in two of the three legs and the potential coils attached respectively between each of these legs and the third one. In the instrument in question, the addition instead of being made arithmetically is made mechanically, in that it is the sum of the efforts of the coils which causes the downward pressure on the valve. The same instrument or simple modification thereof can of course be used for recording the output of two-phase or any other multiphase lines.

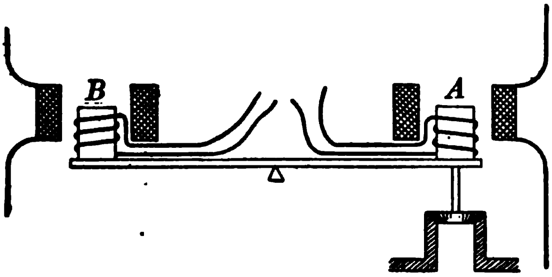

FIG. 258.

In the actual apparatus the contracted passage, *B*, Fig. 256, is formed, not of a long small diameter tube, but of a series of disks of filter paper which are the equivalent of the capillary tube pneumatically, and which have the incidental advantage of removing particles of dust from the air supplied through *A* in the same figure, and so preventing clogging the valve, *D*. The air for working these recorders is supplied either by a small air compressor driven by any suitable means, or through a reducing valve from any high-pressure air supply that may be available.

CHAPTER II.

INTEGRATING METERS.

As has already been stated, integrating meters are devices for registering the product of the mean value of current or power supplied through a given circuit during any given period, by that period. In the great majority of cases they are used to measure the amount of current or energy supplied to the customer of electricity in order to form a just and definite basis for the bills. The name, "recording meters," by which they have long been known, is rapidly falling into disfavor, and the terms "integrating meter" and "electricity meter," both of which describe them more correctly, are coming into use.

Because of the fact that these devices form the basis on which the charges are made by central stations to their customers, the number in use is exceedingly large, and while already many times as great as the number of indicating or true recording instruments employed, is increasing at a rate that is daily becoming larger. As they are subject to conditions under which few of the instruments heretofore described are employed, and as they are inherently of such construction that the wear is greater and the length of time that they will remain in calibration and also their life is shorter, they come under a somewhat different category, and their peculiarities and ills are more appropriately treated in a volume devoted to them exclusively. A brief description of the principles on which the more prominent types are based is, however, thought properly to form a part of a treatise on the general subject of electric measurements and measuring apparatus.

Integrating meters may conveniently be divided into the following general classes: Chemical meters, these being ones in which the desired current data is obtained through electro deposition; motor meters, in which the device showing the current or energy integral is actuated by an electric motor mechanism; and mechanical meters in which a mechanical integrating device like a planimeter is actuated by an indicating instrument and its indications used to show the result.

In all of these it is desired to obtain a record of the total amount of energy passed through the meter, and where the apparatus is an integrating wattmeter, this result is attained directly. Some of the instruments give, however, not watt hours, but ampere hours, and the resultant charge made to the customer is based on the assumption that current has been delivered at a constant potential. This state of affairs, while never actually existing, as the potential at the customer's premises may easily vary 5 per cent, is generally sufficiently close as an average to form a basis of charge that is as equitable as is the watt-hour basis.

CHEMICAL METERS.

Edison Chemical Meters.

The most prominent and practically the only representative of the chemical meters is the Edison meter. It consists of a voltameter in which the plates are of zinc and the solution of zinc-sulphate, instead of copper and copper sulphate, respectively, as in the case of the voltameters, mentioned on page 14. A shunt is inserted in the supply circuit and combined with the meter itself, so that only a known fraction of the total current passes through the voltameter. Two voltameter cells connected in series with each other are usually employed in order to afford a double check, and a thermostat is also added which consists of a compound metallic strip that closes a circuit through an incandescent lamp when the temperature falls too low, so that the heat from the latter may serve to keep the cells from freezing or becoming sufficiently cold to introduce errors.

An Edison chemical meter is shown in Fig. 259.

Instruments of this type possess the very great advantage of containing no moving parts and hence not being subject to deterioration. Their accuracy is also of the highest, as the fact that there is no friction means that the smallest loads are registered with the same accuracy as the greatest ones within their capacity. Further, there is no inertia, so that if the current passed through them is fluctuating in strength, the meter takes account of it all without having that inertia introduce errors because of its refusal to allow the apparatus to get up to speed before the current has again fallen. Its drawbacks are that in order to obtain readings the jars containing the plates must be removed from the meter and carried to some point where the delicate operations of cleaning and drying the plates and weighing the change in weight can be attended to. Where the instrument is in constant use, this means that two sets of voltameters must be supplied, the one being in the recorder while the other is at the station. An incidental, but important, further drawback is that the customer to whom current is being sold and whose bills are figured from the indications of the recorder, is left without even the crudest means for ascertaining what the meter readings are, and is therefore obliged to rely entirely on the accuracy of the station reports as rendered in the form of bills. The comic-paper man with his gas-meter jokes has rendered such apparatus out of the question. Even an instrument which a customer can read himself is viewed with suspicion, and when no means of this kind are afforded it is generally a waste of time and breath to attempt to persuade him that bills are not made up simply by guesswork and with an idea of having them as large as he will stand without protest. It is for the latter

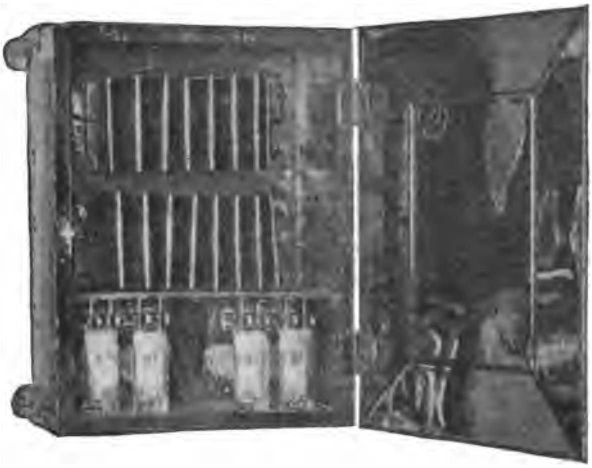

FIG. 259.

reason in many cases, as much as any other, that the Edison meters are going out of use and being replaced by integrating instruments of the motor type.

MOTOR METERS.

Thomson Integrating Meters.

One of the oldest and certainly the most widely used motor meter is the Thomson integrating watt-hour instrument shown with its protective casing removed in Fig. 260. It consists of an electric motor with a vertical shaft, the armature being of the drum-wound type and both it and the field windings being without iron cores. The armature wires are of small diameter and carry a current varying in proportion to the potential between

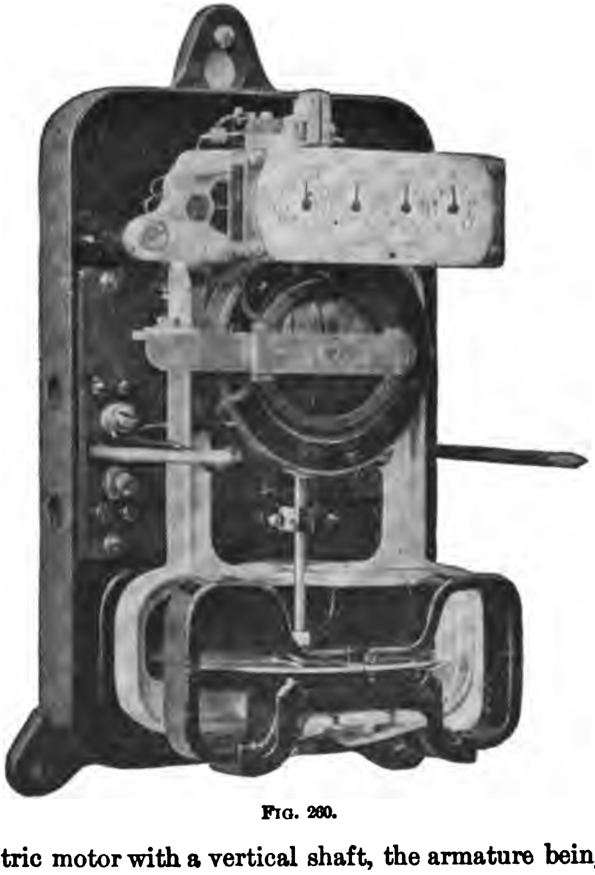

FIG. 260.

the service mains, acting like the potential windings of an indicating wattmeter. The field windings are of heavy wire, and through them is passed the total current. The torque exerted under these conditions is evidently proportional to the product of the simultaneous instantaneous values of the current and potential, that is to say, to the watts, whether the current is direct or alternating. The load for the motor is supplied by a copper disk secured on the lower part of the shaft and rotating between the pole faces of a pair of permanent magnets, the eddy currents generated in the disk by its rotation in this magnetic field forming a drag that increases in strength in direct proportion to the speed. As the torque of the motor increases in direct proportion to the watts, it is clear that each wattage calls forth a corresponding opposing load and that the speed therefore increases in direct proportion to the watts. It is hence possible simply to attach a train of gears to be driven by the rotating shaft and to affix pointers to appropriate members of this train which will thereupon show on appropriately divided dials over which they sweep, the watt hours that have been consumed.

If the apparatus were frictionless, it would operate correctly when made along the simple lines described. This is, however, not the case, as the friction between the bearing on which the foot of the shaft rests, and between the commutator and the brushes, is not an inappreciable quantity. It is, however, a quantity that may safely be assumed to be nearly constant irrespective of the speed of rotation of the shaft, and provision is hence made to supply a constant torque which will just balance this frictional resistance. The means is a coil wound like the stationary field coils, and of a size that will just slip inside of one of them, the coil being of fine wire and connected in series with the armature and the non-inductive calibrating resistance. As the circuit so formed is always connected across the mains, current is continuously flowing through it, and by properly adjusting the distance between the fixed coil and the armature, the field that the coil supplies may be made of a strength that is just sufficient to make the torque of the armature in it one that balances the frictional drag. In practice it is necessary to adjust the position of this so-called "starting coil" after the meter has been erected in place. This is because a meter subject to mechanical vibration has less friction of the lower bearing than if the same instrument were installed at a perfectly quiet point. The adjustment is made empirically, the starting coil being pushed inward toward the armature until the latter just begins to rotate with no current flowing through the series winding, whereupon the coil is slightly retracted and then made fast.

As there are two series field coils the instrument is easily arranged for measuring the input on a three-wire circuit, one of the coils being placed in series with each of the outer mains and the potential coil between one of the outer mains and the neutral, as is shown in Fig. 261.

For very heavy currents such as in central stations, the current windings take the form of a flat copper bar as shown in Fig. 262, and two armatures, each of which is placed within the influence of the field surrounding the bar, are used connected to a common shaft. In all of the instruments the calibration may be adjusted by varying the radial distance between the shaft turned by the armature and the center of the pole faces embracing the copper disk and so changing the opposing torque.

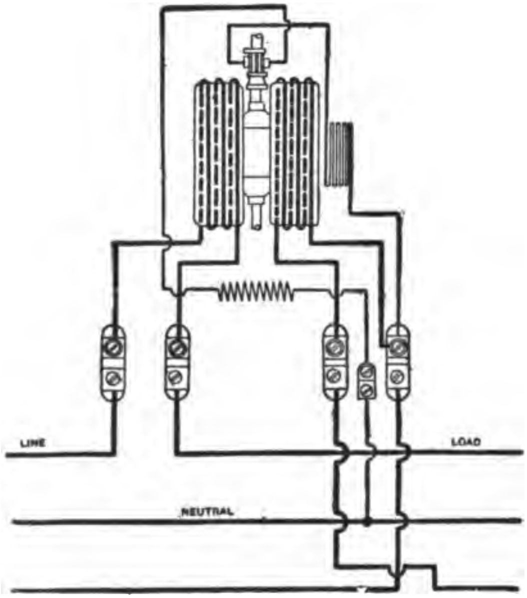

FIG. 261.

Sangamo Integrating Meters.

In this apparatus, as in the Thomson described above, a motor exerting a torque proportional to the watt consumption of the circuit in which it is connected, rotates a disk of conducting material between the jaws of stationary permanent magnets, and the number of its revolutions as shown by pointers sweeping over appropriately divided dials is a measure of the watt hours.

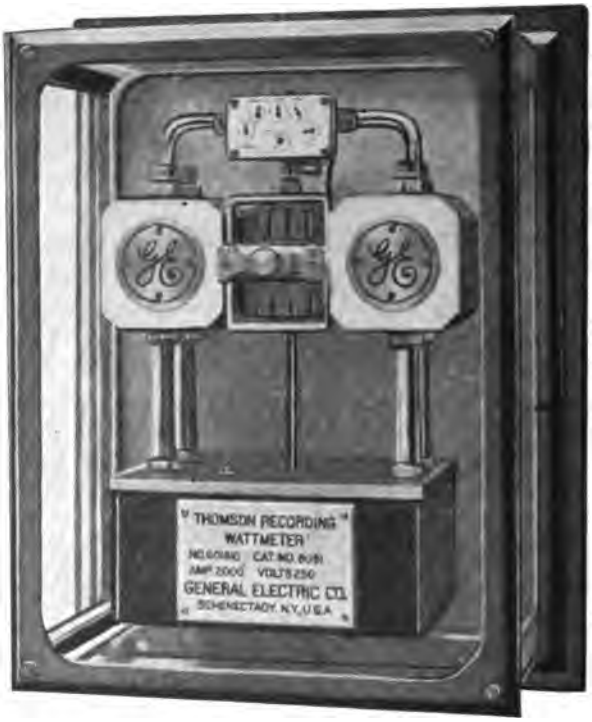

FIG. 262.

The motor element and many of the details of the apparatus differ markedly from the Thomson device. The former will be understood by reference to accompanying Fig. 263. Here a disk, *A*, of copper provided with a float chamber, *B*, is submerged in a bath of mercury, *C*, inclosed in a chamber of insulating material, *D*. Bedded into the walls of the chamber are a block of iron, *GG'*, and the extremities, *EE'*, of a laminated core electromagnet *EFE'*. Copper lugs, *HH'*, are also bedded into the chamber at diametrically opposite points. When such a structure is connected in circuit as the figure shows, the disk, *A*, is evidently located within the field of force of the electromagnet, the flux direction being from *E* to *G* and from *G′* to *E′*. The disk at the same time is being traversed by a current flowing in the direction shown by the arrows, coming in through the lug, *H*, through the short gap between *A* and *H* that is filled with mercury, and similarly out from *A* to *H′*. We thus have an Arago disk motor whose torque is in proportion to the watt consumption of the load under measurement, as the disk current is that required by the load, while the magnetic field against which it reacts is of a strength proportional to the applied potential, the windings of the electromagnet being connected across the supply line.

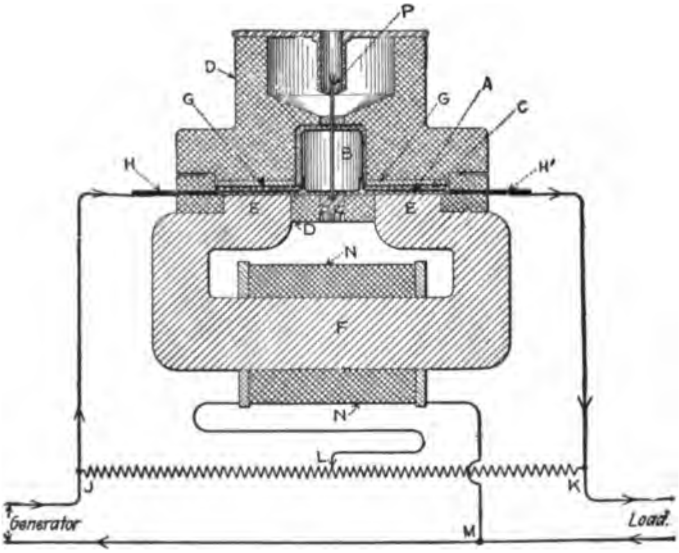

FIG. 263.

In this meter the device for obtaining a small and adjustable initial torque to compensate for the retardational effect of the friction of the moving parts consists of a small spiral of bare resistance wire wound on a hard rubber rod and electrically connected at *J* and *K* in shunt to the disk circuit. Current for the potential circuit of the meter is tapped off from this spiral at any desired point of its length by shifting along the movable contact, *L*. The resistance of the spiral is high as compared with that of the circuit through the disk. With *L* near *J*, the major portion of the current drawn by the windings, *N*, of the potential circuit, evidently flows direct from *J* through *LN* to *M*; a small portion only flowing through the by-path, *JHAH'KL*, owing to the much higher resistance of that path. There is then but a feeble current through the disk, *A*. When *L* is moved over to *K*, the high resistance of the spiral means that the major portion of the potential circuit current flows through the disk circuit instead of through *JK* as before, and similarly for intermediate positions of *L*. The proportions are such that this small current which constantly flows through the disk, independent of the load, may, by shifting *L*, be brought to a value setting up a torque which just balances friction.

The meters are claimed to be superior to the Thomson form. For one thing the commutator, which is always a more or less troublesome element and a source of variable friction errors, is eliminated. For another thing, the buoyant effect of the mercury is utilized to entirely relieve the lower shaft bearing of the weight of the moving system; in fact, the design gives a very slight upward thrust of about two per cent of downward pressure in a non-floated meter. This reduced pressure means greatly decreased friction and wear and a much lessened liability to injury of the jewel or staff end if the apparatus is jarred or run subject to vibration. Another feature is the ability to use shunts similar to those utilized with indicating ammeters of the direct-current type, to increase the ampere capacity. This point is of a decided advantage from the standpoint of cost, as a shunt can be built for a fraction of the expense involved in constructing the stationary conductors in a commutator type meter of material

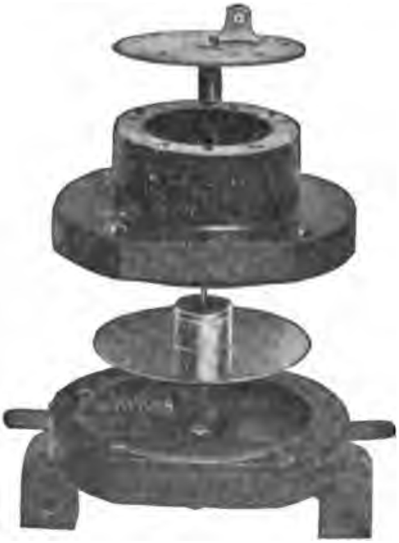

FIG. 264.

heavy enough to carry currents of high value. Shunts are not feasible with commutator apparatus.

Fig. 264 shows the parts of the motor member of a Sangamo meter disassembled and arranged one above the other in the order in which they go together. The downwardly projecting tube on the top cover plate contains a pierced jewel through which the shaft, *P*, Fig. 263, passes and which acts as a guide bearing for that shaft. The fact that the minute clearance between the shaft and its bearing is the only point where mercury could escape, and that the mercury can never get at that point owing to the "patent ink well" type of construction, makes it possible to ship such apparatus from place to place with the mercury in position and without danger of spilling any of it.

A Sangamo meter with the cover removed is shown in Fig. 265.

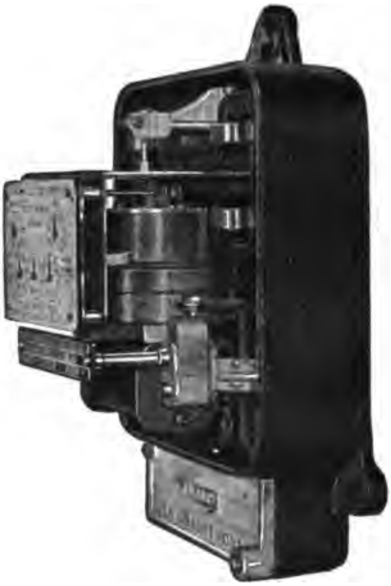

FIG. 265.

Aaron Meter.

The Aaron integrating instrument can be considered as belonging to the class of motor meters only in that the indices which show the current or energy consumption are driven over the dials by spring motors. The apparatus is not in use in this country, and it is doubtful whether it ever will be employed to any extent here, as it is both bulky and costly and rather too complex to suit the fancy of our engineers. Its ingenious principle, however, entitles it to at least brief mention in this volume.

The apparatus takes on many different forms, according to the kind of circuit on which it is to be used, but all rest on the following principle: Two separate clockworks having escapements of the pendulum pattern are mounted together on a common framework, and these are adjusted so that their rate is exactly the same. The two trains of clockwork mesh into two gears, P and P' respectively (Fig. 266), which gears, together with the pinion, I, form a device like the gear in the Callendar recorder illustrated in Fig. 247. As long as the trains are moving at the same rate, P and P' will rotate without causing the shaft that carries I to rotate about its axis, X. If, however, one of the trains should be caused to run more slowly than the other, X will be rotated, and the pinion on it will set the indicating hands attached to the gears in mesh with the pinion which it carries in rotation over their respective dials.

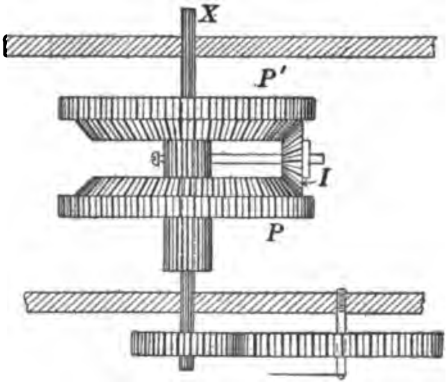

FIG. 266.

A difference in speed of the gear trains of the two clocks is brought about and made to vary in proportion to the strength of the measured current in the following way: Referring to Fig. 267, which shows an Aaron meter with the case open, it can be seen that the left-hand one of the clocks is provided with an ordinary pendulum, this being made of brass or any other non-magnetic material. The bob of the right-hand pendulum is a U-shaped permanent magnet, which swings over the end of a solenoid through which the current to be measured is passed. When no current is flowing the solenoid of course exerts no influence on the magnet, and the clocks are free to run at the like speed to which they are primarily adjusted. When, however, current flows, the swings of the magnet are retarded, and the amount of retardation increases in direct proportion to the current strength.

For alternating-current work, a laminated iron core swinging within a horizontally placed solenoid is substituted for the other arrangement, and for the measurement of watt hours instead of ampere hours the pendulum bob is formed of a coil of fine wire that is connected across the line through the interposition of a suitable auxiliary resistance. As the planes of the fixed and swinging coils are parallel, the attraction between them varies with the watts, as in the case of an indicating wattmeter. Other possible modifications rendering the apparatus suitable for use on three-wire and multiphase circuits will suggest themselves.

ALTERNATING-CURRENT METERS.

The Thomson commutator meter above described and others of its class may be used on alternating as well as direct current, just as a dynamometer type wattmeter is available for either kind of circuit, but they are but seldom so employed in practice, principally because the commutator with its attendant ills and the heavy duty on the jewel bearing because of the great weight of the moving system, are considered evils to be tolerated only where their presence is essential. The Sangamo meter in which, as explained, the commutator is absent and the jewel pressure extremely small, forms an acceptable alternating-current device when a condenser is inserted in the potential circuit to compensate for the self-induction of that winding and cause the changes in magnetization of the iron core to vary in phase with the line potential. This pattern is relatively new, but seems growing in favor.

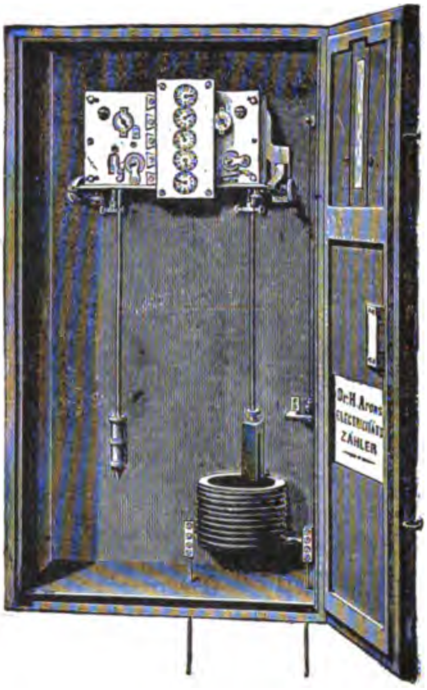

FIG. 267.

The class of meter for alternating-current service in most extensive use is, however, the induction type, which, while operative only on alternating circuits, is attractive because of its simplicity and durability.

The earliest form of induction meter that came into general service is the

Shallenberger Meter.

The Shallenberger meter records ampere hours and, as is seen from Fig. 268, contains a stationary flattened coil of heavy wire through which the current to be measured is passed. Within this coil there is a second one similarly shaped, and placed with its longitudinal axis at an angle to the above series coil and having its windings short-circuited on itself. Located in the plane of both coils is an aluminum disk. The alternating current flowing through the outer coil produces another current in the short-circuited one, and the resultant of the magnetic fields set up by the two is evidently shifting around the axis of the inclosed disk. This rotating field carries the disk along with it, the torque being directly proportional to the current in the series coil. The torque opposing the rotation of the aluminum disk is furnished by four light vanes of aluminum secured to radial arms, forming a fan whose opposing torque varies as the speed and the work necessary to rotate it, as the square of the speed. The revolutions of the rotating element are registered by a train of gears driven by the rotating shaft as in other motor meters.

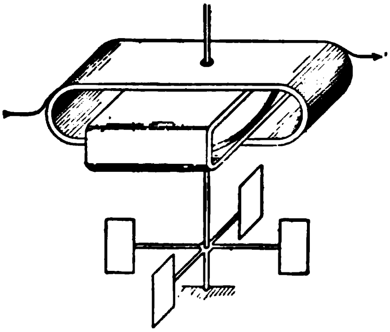

FIG. 268.

Induction Wattmeters.

The Shallenberger meter above mentioned is evidently an ampere-hour meter. Induction instruments may be built to register watt hours instead by causing a rotatably mounted disk or drum of good conducting material, usually aluminum, to be acted upon by two sets of coils, one carrying the line current and the other a current varying in proportion to the applied potential and hence connected across the line. In order that these two currents may set up a rotating magnetic field so as to carry the aluminum disk along and thus drive the train of gears actuating the indices which show the watt hours consumption, one must be displaced in phase from the other. This is accomplished in commercial meters by placing in series with the potential winding, which is connected across the line, a highly inductive resistance which of course causes the phase of the current flowing therethrough to be displaced nearly ninety degrees. The torque exerted on the rotatable member is proportional to the product of the simultaneous instantaneous strengths of the currents in the two windings, that is to say, to the watts being expended in the circuit beyond.

The mechanical disposition of the elements of such meters evidently admits of considerable variation.

MECHANICALLY INTEGRATING METERS.

A type of integrating meter possessing many attractive features and which is periodically re-invented, consists in transferring the indications of an indicating ammeter or wattmeter to a clockwork or motor-driven counting train. The needle of the indicating instrument swings over a scale as usual and carries a stop or else some transmitting device. A clockwork operated mechanism is set in motion at successive intervals of time, and either rotates through a distance determined by the position of the stop as determined by the load passing through the instrument, or works the counting train through a transfer gear carried by the needle for a length of time that is likewise determined by the needle's position.

The number of such devices in actual use is so exceedingly small that the devotion of any extended space to them and their peculiarities and drawbacks is not warranted. Mention is made as the principle at least is of interest.

BOYLE INTEGRATOR.

Another form of integrating meter in which the mechanism of an indicating device is utilized is the recorder mentioned on page 314. To the rod which carries the record pen and the index that sweeps over the graduated scale, there is secured, as is seen from Fig. 269, an arm with a fork-shaped end which in rising carries with it a small wheel, *A*. *A* is free to slide along the shaft, *B*, which has at its end a worm that drives the counting train. *A* drives *B* in that the latter is provided with a key-way running for its whole length, *A* being supplied with a feather that runs in it. *A* is in contact with the face of a large disk, *D*, that is driven by clockwork at a constant speed, and the plane of whose face is at right angles to that of *A*. When *A* is at the center of *D* the latter will rotate without causing *A* to turn; when, however, *A* is carried above the center by the fork *F*, *D* will drive it and hence the counting train, and the rate of rotation will be in direct proportion to the distance of *F* from the center. The latter distance is proportional to the current through the meter which controls the position of the needle, *E*, on the scale, *S*, and the counting train hence gives ampere or watt hours according as that meter is an ampere or a wattmeter.

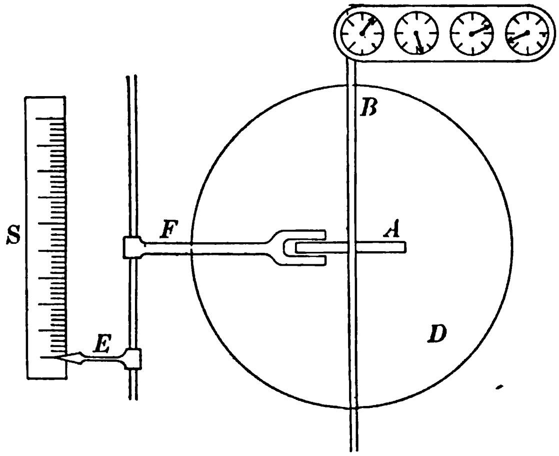

FIG. 269.

CHAPTER III.

MAXIMUM DEMAND METERS.

In order to be able to charge the purchaser of electrical energy an equitable amount, it is desirable to know not only the product of the mean value of the energy by time it was supplied, but also to know the maximum amount that has been called for during any appreciable period, in order that the purchaser may be properly taxed for that proportion of the total supply equipment that must be held in reserve for him, so that he may make that demand at any time. Instruments for measuring this largest call are known as maximum demand, or simply demand, meters.

Wright Maximum Meters.

This instrument, which is illustrated in Fig. 270, consists of a U-shaped glass tube, having enlarged chambers at both extremities and a side tube opening out of one of them. The chamber that has not the side outlet is surrounded with a couple of turns of high-resistance alloy that is made in the form of a thin ribbon wound tightly about the chamber, in order that the heat generated therein by the passage of the current may warm the air in the chamber. The tube is filled with liquid to about the height shown. When current flows through the resistance strip the expansion of the air in the chamber, *A*, due to the heat, forces the surface of the liquid in the left-hand leg of the tube downward, and that in the right-hand one correspondingly up

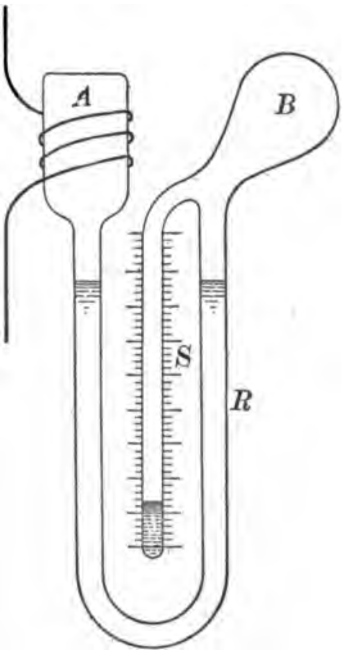

FIG. 270.

ward. Should the current strength be sufficiently high, the surface of *R* will rise until the liquid will overflow into the central tube, *S*. If the current is then reduced or cut off, and afterward put on again, *R* cannot rise sufficiently to overflow into *S* unless the current strength is greater than the preceding one. The greater the current, however, the greater is the amount of liquid that will flow into the center tube, and the scale placed alongside of the tube may, therefore, be graduated to show the maximum amperage that has passed through the heater strip. The air in the chamber, *A*, does not heat up instantaneously, and the surface of *R*, therefore, does not vary at once with change in current strength, but lags considerably behind it, the time element being such that if a given current flows through the winding for five minutes, only about 80 per cent of the amount of liquid will flow into *S* that would get there if the current were left on indefinitely: about 95 per cent of the total amount will be measured in ten minutes, and all of it in half an hour. This feature is of importance, as it means that the customer is not penalized because of the existence of a momentary short circuit on his line, which does not injure the supply station in any way, and account is not taken of a heavy current momentarily drawn, as when starting a motor, which also does not inconvenience the station.

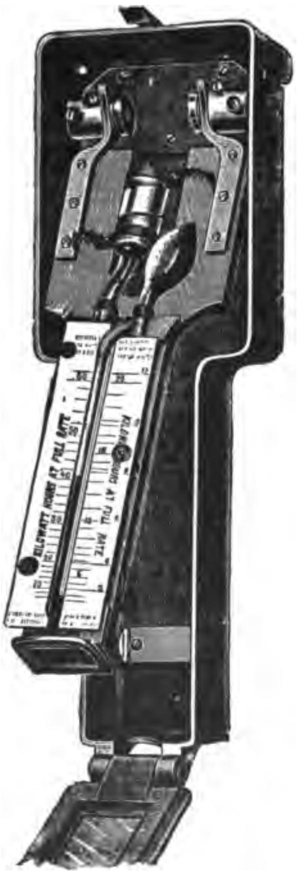

Fig. 271.

The meter can be reset, that is, the liquid drained out of the tube, *S*, by inverting the U-shaped portion so that it all flows into the chamber, *B*, as after it is lowered to its original position again that liquid will flow into *R* instead of *S*. Variations in the temperature of the atmosphere do not affect the device, as it is in reality simply a maximum indicating differential thermometer actuated by the difference in temperature between its two bulbs. The apparatus is put in a locked case, so that this resetting cannot be done by unauthorized parties. A complete instrument is shown in Fig. 271.

Schattner Maximum Meter.

In this device, illustrated in Fig. 272, a glass tube bent as shown is partially filled with steel balls which fit its bore quite closely, and then entirely filled with an oil of greater or less viscosity, according to the lag in indications desired, after which it is sealed. This tube is then secured by clips to the sector-shaped plate carried by a suitably journaled shaft, which shaft is rotated over an angle proportionate to the strength of the current flowing through the curved solenoid in the lower left-hand corner of the containing case because of the attraction of that solenoid on its iron core. As the sector and hence the tube are so tilted, the steel balls, which are initially all contained in the tube's curved arm, tend to run out of this arm and down into the straight one. The curvature is such that for a small inclination

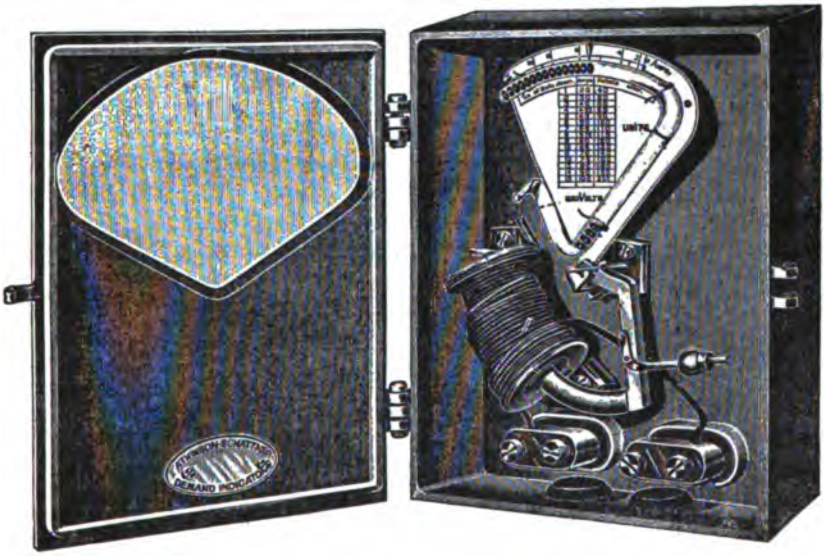

FIG. 272.

only one ball is on a downward grade and that the number so situated increases with the angular deflection of the sector. The oil in the tube gives a dashpot effect to the movement of the steel balls such that a momentary overload or short circuit would not be registered, that is to say it introduces the same time lag that exists in the indications of the Wright meter. Different lags are obtained by using oils of different viscosities.

On the face of the sector is printed a table as shown, giving the ampere flows through the solenoid required to cause varying numbers of balls to run down into the straight tube. The sector also has marked on it just above the curved tube, a scale graduated in amperes, the position of said scale relative to a stationary pointer carried by the containing case, thus giving a means of reading the instantaneous values of the current strength.

This meter is reset, that is, the balls returned to their initial positions in the curved arm after taking a reading by removing the tube from its clips and hanging it upside down. As this operation is rather a slow one, a spare tube is often supplied fastened in an inverted position inside of the case, and this is exchanged for the first one as readings are made.

PART III.

CHAPTER I.

MAGNETIC UNITS.

THE elementary magnet is a straight thin rod or bar whose manifestations of maximum magnetic energy are exerted at or near its ends at points known as the magnet poles. All magnets have two poles, which are termed by convention positive and negative, the former being that which points toward the north if the magnet is freely suspended in the earth's magnetic field. Magnetic poles of like sign mutually repel one another and poles of unlike sign attract one another with forces that in both cases are directly proportional to the product of the strengths of the two poles and inversely proportional to the square of the distance between them.

UNIT MAGNETIC POLE.

The unit magnetic pole is taken as one which will act on a pole of like strength with a unit of force (1 dyne) when placed at a unit distance (1 cm.) therefrom.

POLE STRENGTH.

The paths in the space surrounding a magnet, throughout which magnetic actions of equal force exist, form closed curves starting from one pole and extending through the surrounding medium back to the other. They are the lines seen when iron filings are sprinkled on a piece of glass or paper under which a magnet is placed, as in the familiar illustrations found in every text-book of physics. When it is desired to ascertain their direction it is done by this sprinkling method, or, when that is not feasible, by suspending a very short and very thin magnetized needle so that it is free to assume any position and plotting its successive directions when moved about in the field to be explored. Such a needle is shown in Fig. 273.

Although the number of paths is infinite for every magnet, by convention lines of force are utilized to designate the strength of the magnetic field as well as to show its direction, one line of force per unit of area (1 square cm.) at right angles to its direction being taken as representing the unit force. This unit force is that exerted by a unit pole at a distance of 1 cm. As the surface surrounding the ideal unit pole is a sphere and has an area of $4\pi r$, and as r is unity at the unit distance, the number of lines of magnetic force that proceed from a unit pole is 4π, which is thus the unit pole strength; its symbol is usually written m.

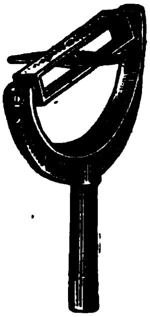

FIG. 273.

STRENGTH OF FIELD.

The strength or intensity of a magnetic field at any point is measured by the force that it would exert on a unit magnetic pole placed at that point, and therefore under the above convention is the number of lines of force per square cm. there. Field strength is designated by the symbol H.

MAGNETIZING FORCE.

Usually the force causing a magnetic flux through a given circuit is supplied by a coil or solenoid of wire through which an electric current is being passed. If that solenoid has a length which is great as compared with its diameter, the directions of the lines of force within it will be parallel except at the ends. If the coil has N turns, its length is L, and the current through it is expressed in absolute units (1 absolute unit equals 10 amperes) the magnetizing force of the solenoid exerted on the medium within it is $\frac{4\pi NI}{10L}$; for if a unit pole were moved along one of the lines of force within the solenoid for a distance of 1 cm. its 4π lines would cut $N \div L$ turns of wire, generating an E.M.F. of $\frac{4\pi N}{L}$ and the work done would be $\frac{4\pi NI}{10L}$.

This is the strength of the field within the coil, and is, therefore, also the H above. The number of turns per unit of length of the solenoid is often written n, that is, $\frac{N}{L} = n$; in this case the above formula becomes $\frac{4\pi nI}{10}$

MAGNETIC INDUCTION.

If the core of the above solenoid were of a magnetic material, say iron, instead of air, while the magnetizing force H would remain the same, the flux of magnetic force through the core would become very much greater. The value of this induced flux is dependent not only on the nature of the material forming the core, that is to say, whether it is of iron, steel, cobalt, etc., but on the magnitude of the magnetizing force, *i.e.*, on the value of H. Flux density is designated by the symbol B, and its unit, the Gauss, is one line of force per square cm. of cross-section.

PERMEABILITY.

The ratio of the magnetizing force to the magnetic induction, that is, of B to H, is the magnetic permeability, and is usually written μ. If the core within the solenoid is made a vacuum, H equals B and μ equals 1.

The permeability of all gases, liquids, and solids, with the exception of nickel, cobalt, and iron and its compounds, is at ordinary temperatures practically that of the vacuum that is used as the unit. No known substance has a permeability of zero; that is, there is no known substance that will prevent the flow of a magnetic flux, and none has a sufficiently low value of μ to be considered as a magnetic insulator in the sense that glass, rubber, etc., are electrical insulators.

MAGNETOMOTIVE FORCE.

The magnetizing force that drives a flux through a reluctance is called a magnetomotive force. As the magnetizing force H is simply the magnetomotive force per unit of length of the magnetizing coil, the value of the magnetomotive force of a given coil is H, L, or as $H = \frac{4\pi NI}{10L}$ is $\frac{4\pi NI}{10}$. Magnetomotive force is expressed in gilberts, and, as is seen from the formula, a gilbert is .7958 ampere turns. Its symbol is F.

MAGNETIC MOMENT.

If a straight-bar magnet is freely suspended in a uniform magnetic field it will take up a position such that its axis is parallel to the lines of force. The turning moment tending to bring it into parallelism is a maximum when the bar is at right angles to the field and is dependent on the distance between the magnet poles, the strength of the poles, and the strength of the field. If H, the field strength, is unity, the moment, M, of the magnet is the product of the strength of either pole by the distance between them, that is to say, it is ml.

INTENSITY OF MAGNETIZATION.

The intensity of magnetization, J, of a magnet having its poles at its ends is the pole strength, m, divided by the polar area S. It is also the magnetic moment, M, of the magnet divided by its volume, V, for if l is the length, $V = lS$, or $S = \frac{V}{l}$. The moment is $M = lm$, or $m = \frac{M}{l}$. Substituting these values in the formula for pole strength, we have $\frac{m}{s} = \frac{M}{v}$.

The relations in a magnetic circuit are governed by the law: flux equals magnetomotive force divided by reluctance, a formula that is easily recognized as being analogous to Ohm's law for electric circuits.

CHAPTER II.

MEASUREMENT OF FIELD STRENGTH.

BY CALCULATION.

The strength of the magnetic field within a solenoid having a non-magnetic core may be calculated directly from the formula $H = \frac{4\pi NI}{10L}$ given on page 344. The number of turns, N, is counted, the length of the solenoid, L, is measured, and the current, I, read with the aid of any appropriate current-measuring instrument.

Where the field to be measured is that of a permanent magnet, or where for other reasons the method of calculation cannot be employed, means of direct measurement must be resorted to. The first of these is the

METHOD OF OSCILLATION OF A MAGNET.

This is due to Gauss and is suitable only for the measurement of very weak fields, as, for instance, that of the earth. Two sets of observations must be made, the first being the time of oscillation of a suspended magnet, and the second the deflections of that magnet when acted on by the field of another. The first gives the value of the product, MH, from the formula $\frac{K\pi^2}{t^2(1+\theta)} = MH.$ In this formula K is the moment of inertia of the magnet, t the time of a single oscillation of the magnet, and θ the ratio of torsion of the supporting thread. If the magnet is a simple geometrical body and known to be homogeneous, its moment of inertia can be calculated from its weight and dimensions in the ordinary way. If it is irregular the following expedient may be adopted. The time of a single oscillation, with the magnet in its original condition, is first observed and recorded. It is then loaded with a ring whose mass and dimensions are known, and whose own time of inertia can therefore be calculated. The magnet loaded with this ring is then set swinging and the time of an oscillation noted as before. If this time be called t_1 the value of $MH = \frac{\pi^2 K}{(1+\theta)(t^2 - t_1^2)}$. The ratio of torsion in the formula is the ratio between the restoring forces due to the elasticity of the suspension and to the action of the magnetic fields respectively when the magnet is only slightly deflected from the magnetic meridian. To find its value, the torsion head attached to the suspension carrying the magnet should be twisted through an angle of about 360 degrees and the resulting deflection noted. If the angle of twist of the torsion head is called a and that of the deflection b, $\theta = \frac{b}{a-b}$. The time of oscillation, t, is best observed with the aid of a stop-watch and a telescope and scale or lamp and scale arrangement, such as that used with reflecting galvanometers (see page 42).

The second observation in the oscillation method of measurement of weak fields is that of the ratio of M to H. To obtain it, it is necessary to use a magnetometer, a device for comparing the magnetic moments of different magnets. The magnetometer consists of a light silvered mirror, to the back of which are cemented two or three short strips of magnetized watch spring which serve as a small magnetic needle. This will of course hang with its plane in the magnetic meridian. The magnet, whose time of oscillation has been determined, is now placed with its axis at right angles to the axis of the magnetometer needle and will thereupon cause the magnetometer reading to change. The angular deflection of the magnetometer is noted, as is also the distance between the center of the test bar and the instrument. Call the distance between the center of the magnetometer needle and the magnet r. The operation is then to be repeated, using a different value for the distance between the magnetometer needle and the bar. Call this distance r_1 and let the corresponding angular deflections be ϕ and ϕ^1. The value $\frac{M}{H}$ is then

$$\frac{M}{H} = \frac{r^5 \tan \phi - r_1^5 \tan \phi^1}{r^2 - r_1^2}.$$

In testing any weak field extreme care must be taken to see that there are no bodies of magnetic material in the immediate vicinity of the apparatus, and that there are no movable magnetic masses, even if they are nothing but a bunch of keys carried in the pocket, as either will seriously modify the field and introduce large errors in the results. The conditions are particularly difficult when measuring the intensity of the earth's field, as this is always varying slightly in itself and is much influenced by the fields due to current-carrying conductors.

INDUCTION METHODS. (SNAP AND ROTATING COILS.)

If a conductor consisting of N turns of wire and inclosing an area, S, is placed in a magnetic field of uniform intensity, H, it is traversed by a total flux, SH, if its plane is at right angles to the direction of the lines of force. If this coil is sharply rotated through 180 degrees about a diametral axis, an E.M.F. will be induced therein having a value of $2NSH$. This E.M.F. lasts but momentarily, and a ballistic galvanometer must be utilized if it is to be observed. Suppose such a galvanometer to be attached to the terminals of such a coil, and that galvanometer resistance is g. Let the resistance of the coil be r and that of the leads plus any auxiliary resistances that may be placed in the circuit in order to bring the galvanometer deflection down to a reasonable point be R. The E.M.F. generated by the rotation of the coil would then cause the quantity of electricity $q = \frac{2NSH}{g+r+R}$ to flow through the galvanometer circuit. The value of H can be calculated directly from this formula if the galvanometer constant is known. The latter can be found for any particular instrument by discharging a condenser through it, in the usual manner.

If the gap in which the field to be measured exists is so narrow that it is impossible to rotate the coil of wire, it can be sharply moved by hand at right angles to the lines of force or the same thing accomplished with a trigger-released, spring-actuated device. In this modification the formula becomes $q = \frac{HSlN}{g+r+R}$, in which l is the distance through which the coil has been moved.

This latter method must be used in the narrow clearance space existing between the armature and the pole pieces of a dynamo or motor, and the coil is usually moved, not between two fixed limits, but between a position in the gap and one outside of it where the field does not exist, as this is easier than attempting to arrest a coil suddenly and accurately.

The rotation method is more convenient when there is sufficient space to allow of revolving the coils, and is specially useful in measuring the intensity of the stray field of generators. If the angle of rotation is made exactly 180 degrees, the results obtained are very reliable.

The rotating coil method may also be used for the determination of weak fields such as that of the earth if the coil area S is made very large.

BISMUTH SPIRAL.

The metal bismuth has the peculiar property of offering an increased electrical resistance when placed in a magnetic field. The intensity of the field can be measured from this increase in resistance, being proportional to the difference between the resistance when in the field and when out of it divided by the resistance when out of it. The actual apparatus for measuring field strength in this way takes the form of a flat spiral of bismuth wire doubled back on itself, so as to avoid induction errors, and attached to a handle as shown in Fig. 274. The windings are held in place by being cemented between two plates of mica and form a coil so thin that it can easily be introduced into the clearance space between an armature and its field magnets. The resistance of the coil when not within the

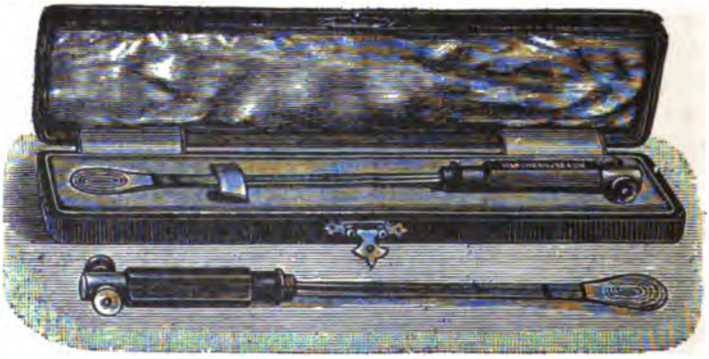

FIG. 274.

influence of a field is usually made about 10 ohms. The relation between the field strength and resistance is determined separately for each spiral and remains sensibly constant under all commercial circumstances. The varying resistance is easily determined with the aid of a bridge, and the field strength found by consulting a table or curve which comes with the coil, or in some instances, by having the bridge specially calibrated, so that when used with a given spiral the values of *H* are indicated directly. Fig. 275 shows the calibration curve of an average specimen.

ELECTROMAGNETIC METHOD.

In the commercial ammeters and voltmeters of the permanent magnet pattern described in Chapter VI, current strength is measured by the reaction between a constant field and the unknown current, as indicated by an index attached to a moving coil working against a spring which offers an opposing force like the spring in a spring balance. It is evident that the reverse of this method can be used to measure the strength of the field if the strength of the current flowing through the movable conductor is known. An apparatus based on this principle is shown in Fig. 276. Here a conductor, *l*, is rigidly attached to an arm, *C*, a known current measured by an ammeter being passed through *l* by means of the flexible strips *ff'*. If *l* is introduced into the gap in a magnetic circuit so that the current through it flows at right angles to the lines of force, it will be acted upon by a force *IHl* in which *I* is the current, *H* the field intensity, and *l* the length of the conductor. The force is measured by varying the tension of the spring *R* by turning the screw *V*.

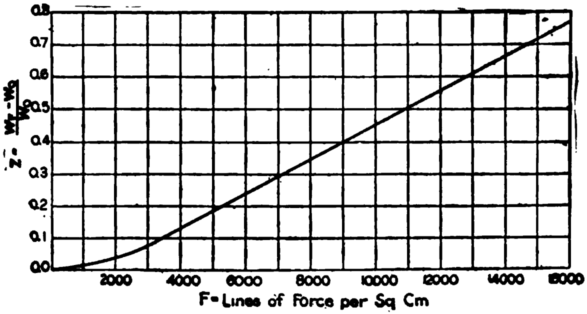

FIG. 275.

The screw is calibrated so that the force exerted is known and a micrometer index attached to it can therefore be made to indicate field strengths directly with the current I adjusted to a given value.

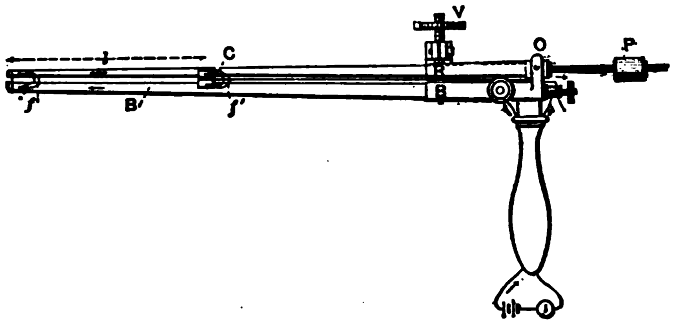

FIG. 276.

The shortness of the length, l, and the small current that may be passed through it because of the necessity of making the conducting strips, ff, so thin that they offer no appreciable resistance to l's movement, makes the forces involved small, so that such apparatus can be used only for the measurement of powerful fields.

Various modifications of this apparatus dependent on the reaction between the field and a current-carrying conductor will suggest themselves.

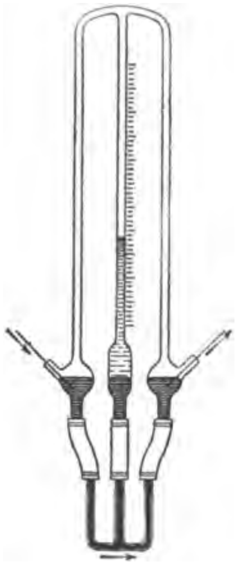

FIG. 277.

MIOT INDUCTIOMETER.

An interesting piece of apparatus for measuring field strength is the Miot Inductiometer illustrated in Fig. 277. It consists of a three-legged glass tube filled with mercury to the level shown by the heavily shaded areas. A similarly shaped but shorter three-legged tube is attached to its lower end by means of rubber tubing, so that it can be placed at any desired angle to the upper one. The lower member of the short tube is placed in the field whose strength is to be measured and current passed through the mercury contained therein in the direction indicated by the arrows. The position of the lower tube is made such that the flow of current traverses the fields perpendicular to the lines of force, and therefore the reaction between that field and the current through the mercury causes the latter to rise in the central tube. The elevation of the mercury there, as indicated by the rise in the surface of the column of liquid that is poured over its surface, is proportional to the field strength and to the current through the mercury, in other words, H equals KhI. K is a constant which is separately determined for every inductiometer, n is the head of liquid as measured by the scale placed alongside of the central tube, and I is read from an ammeter placed in the current circuit. For any given current the scale can evidently be divided so as to show H directly.

CHAPTER III.

MEASUREMENT OF PERMEABILITY.

THE determination of the permeability, μ, of various specimens of magnetic material is of the utmost importance in the calculation of electrical machinery, as on this quality depends the magnetizing force that must be supplied to obtain a magnetic field of sufficient strength to obtain the desired reactions.

It is more difficult to make this determination than that of electrical conductivity, chiefly because of the fact that a joint in a magnetic circuit such as must be used in the majority of permeability measuring devices has, unless made with extreme care, a magnetic resistance that is so high as compared with that of the iron that errors amounting to over 100 per cent are only too readily introduced. Take, for instance, a case in which the air gap between two of the magnetic conductors forming the circuit is as small as .01 mm.; if μ is 2000 this is the resistance of a four millimeter length of the iron and means that a corresponding error will be present in the result. It is therefore clear that with short specimens great pains must be taken to obtain a perfect magnetic contact, machining the surfaces as true as possible and then tightly clamping them together by appropriate devices such as screws, etc. Another difficulty in permeability measurements is that, as already stated, there is no magnetic insulator, and hence no way of confining the flux to a given path, so that leakage factors of unknown magnitude must be allowed for.

As the value of μ varies with different values of the magnetizing force, it is necessary, in order to obtain a complete record of the behavior of a given specimen, to subject it to fields of varying intensities. A specimen should first of all be entirely demagnetized; to accomplish this, it is surrounded by a magnetizing coil through which an alternating current is passed of a value such that the bar will be magnetized more strongly than it has been since subject to the last magnetization. The current should then be gradually decreased in strength by inserting an external resistance until it is reduced to the lowest possible value, whereupon it should be cut off. The minimum value of the demagnetizing current should be made very low indeed, this being conveniently accomplished by utilizing a liquid resistance, in which the distance between two plates immersed in an electrolyte may be constantly increased until one plate is finally withdrawn.

The bar is now magnetized by passing a small current through the surrounding solenoid and observing by one of the methods to be described later on the flux induced therein.

The exciting current is then increased by successive steps and the various values of *B* corresponding to different ones of *H* plotted in the form of a curve. A set of such curves from soft steel, wrought iron, and cast iron specimens is shown in Fig. 278. It will be noted that in each case the value of *B* increases with an increase in the value of *H*, at first quite slowly, then more rapidly to a maximum rate, and finally more slowly again. If the curve were prolonged at the upper end it would be found that a value of *H* would soon be reached at which the curve became a straight line, *B* increasing in direct proportion to *H* only and the iron thus acting like an air core. At this point the iron is said to be "saturated."

For reasons that will be made apparent in the chapter on hysteresis, it is necessary in all permeability tests to see that the strength of the magnetizing current is increased from each step to the next and not allowed to first fall and then rise to the new value.

MAGNETOMETRIC METHOD.

The permeability of a given specimen may be determined with the aid of a magnetometer as follows: —

The specimen should be a rod having a length at least four hundred and preferably as much as five hundred times its diameter, and be enclosed in a magnetizing coil which is slightly longer than itself. The rod should be placed vertically at a known distance from a magnetometer. The solenoid that energizes the bar in itself affects the magnetometer, and this action must be compensated for by the addition of coreless solenoid placed with its axis horizontal in a position found by experiment where the current passed through it, and the bar solenoid in series no longer produces any effect.

It is generally found that the vertical component of the earth's magnetism acts on the test specimen also, and this must then be compensated for by an auxiliary winding through which a current of appropriate strength is kept flowing. A rheostat is inserted in the circuit energizing the vertical compensating winding, and another in that of the bar energizing solenoid, so that the value of *H* may be adjusted at will, the whole apparatus being connected as shown in Fig. 279.

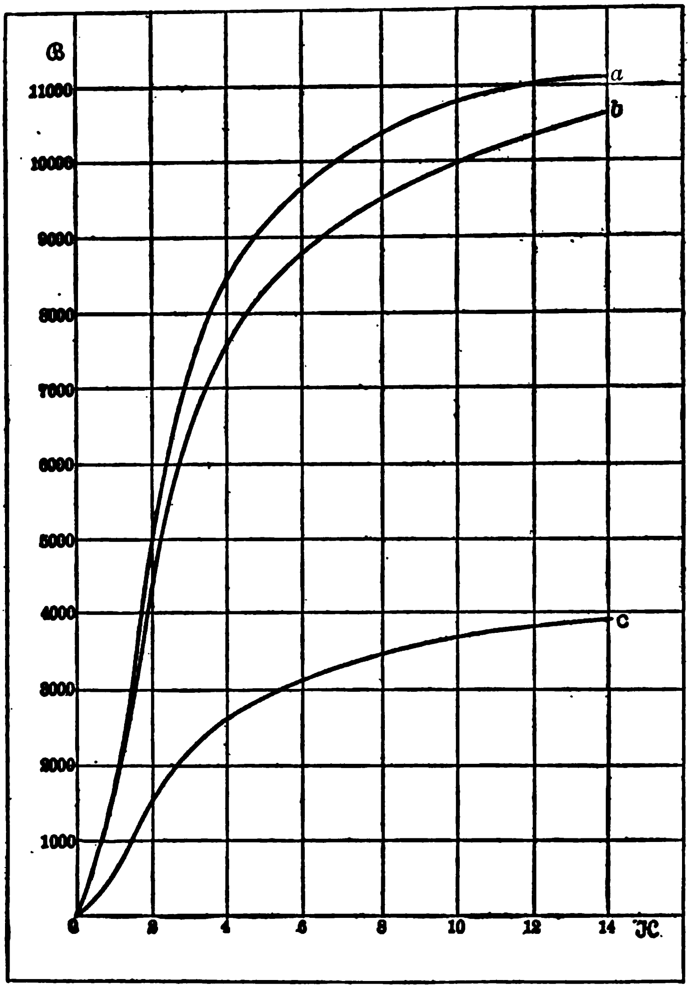

FIG. 278.

After being set up, the compensation for the effect of the main solenoid on the magnetometer is accomplished by shifting the coil as already indicated. The adjustment of the current through the solenoid that compensates for the vertical component of the earth's field is affected by first causing the maximum current to be employed to flow through the main winding and then gradually decreasing it to zero by increasing the resistance in the rheostat *R*, the current being rapidly reversed at the same time by means of a suitable commutator. If the magnetometer shows no traces of magnetism of the bar when *R* has reduced the current value to zero, the strength of the current through *a b* is correct; if action does exist, the strength of the current through *ab* must be adjusted until this disappears.

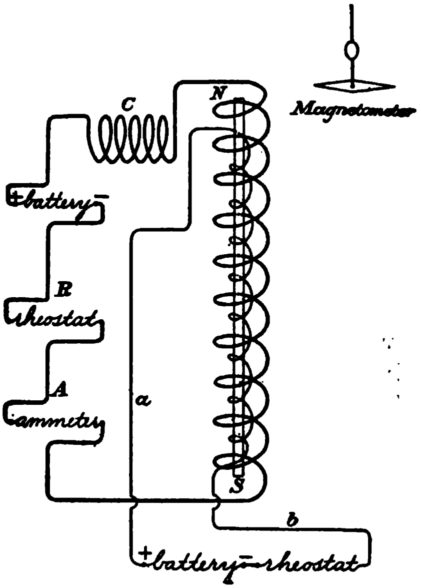

FIG. 279.

We now have the equipment so arranged that the strength of the magnet *N S* can be measured by the magnetometer, this being obtained in terms of the strength H_e of the earth's field at the point of observation. The test bar is so long that its poles may safely be assumed as being at the extreme ends, and the distance between the poles is so great that the magnetometer may be considered as being influenced by the upper one only.

To obtain the curve showing the value of μ the magnetizing current is increased in the desired number of steps and the corresponding values of the induction plotted. The value of H, the magnetizing force, is obtained from the formula $\frac{4\pi nI}{10}$, which has already been given.

Owing to the fact that it is necessary to know the value of the earth's field where the permeability test is being made by magnetometric method as well as to the complication of the apparatus involved, and the fact that the test bar must be of dimensions such that it can rarely be a piece selected from material that is to enter into the construction of electrical appliances, this method is but seldom used outside of a laboratory. Its chief value is in the determination of the permeability at very low magnetizing forces, as these act sluggishly and the magnetometer will record the final effect, whereas in most of the other methods to be described further on such is not the case.

BALLISTIC METHODS.

In the snap coil method of measuring field strength the E.M.F. induced in the coil by its movement through the field as indicated by a ballistic galvanometer is used to determine the strength of the field. As relative motion between the coil and the magnetic flux is all that is necessary, the same results may be had by keeping the coil stationary and causing the flux circuit to collapse, so that the lines of force cut the coil.

Straight Bar Ballistic Test.

If the specimen to be measured can be supplied in the form of a long thin rod of the dimensions mentioned in the preceding paragraph, its permeability can be determined with a ballistic galvanometer as follows:

The bar is placed within a magnetizing solenoid as before, but wound around the center of the solenoid there is placed an auxiliary winding of several turns of wire whose terminals are connected to the ballistic galvanometer. If current is suddenly sent through the solenoid, or if a current already flowing through it is abruptly interrupted, an E.M.F. will be induced in the test coil, which will be shown by the deflection of the ballistic instrument. If K is the galvanometer constant, I the current strength, and N the turns per centimeter length of solenoid the value of B can be found from the equation $B = K\frac{4\pi NI}{10} \times \frac{s}{S}$ in which s is the galvanometer throw with the test bar in place, and S the same before the bar was inserted. Successive values of μ are obtained by making as many successive readings.

Rowland Method.

In this the specimen to be tested must be circular in shape having a small radial breadth. This ring is covered by hand with a known number of turns of wire, and the strength of the current flowing therethrough may be regulated as desired by means of a rheostat, and measured by an ammeter, as shown in Fig. 280. Over a section of the magnetizing winding there is wound a test coil of several turns of fine wire having its terminals connected to a ballistic galvanometer.

In making the test the ring must first of all be thoroughly demagnetized by the method outlined above. Current is then caused to flow through the energizing winding, and when this is suddenly made or broken the change in flux will produce currents in the exploring coil, and these, as indicated by the galvanometer, form a means of obtaining the data sought. The value of H is $\frac{4\pi nI}{10\,l}$ as above, and of B, $K\frac{R\theta\,10^8}{2\,an}$ in which K is the galvanometer constant, R the resistance of the test coil circuit, θ the throw of the galvanometer, a the cross-sectional area of the ring, and n the number of turns in the test coil. From the two we have the value of μ.

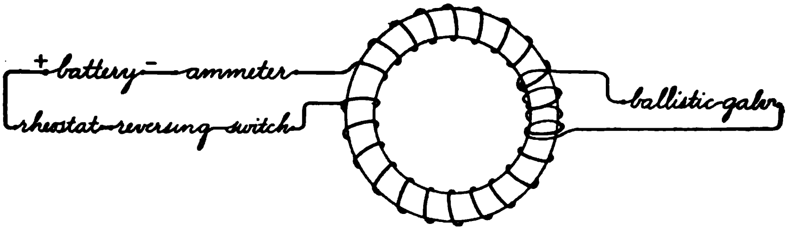

FIG. 280.

While it is easier to make the test specimen in the form of a ring than to obtain the long straight bar, the inconvenience of placing the winding on it by hand is so great that this test is seldom resorted to. A modification which overcomes this disadvantage is the

Hopkinson Divided Bar Method.

Here the test specimen takes the form of a rod again, but one of convenient dimensions, usually about one half inch diameter by 14 to 18 inches length, cut into two parts. This rod is inserted into holes drilled in a very heavy wrought-iron yoke, as illustrated in Fig. 281. The right-hand half of the bar is solidly secured in place by means of a clamp screw, but the left-hand one may be pulled out by means of the handle shown. The exciting coil supplying the magnetomotive force to drive the flux through the specimen is in two parts, wound on appropriate bobbins, and separated by a space sufficient to admit of the insertion of another and so-called test coil wound concentrically with the exciting coil. The exciting current is taken from a set of batteries, measured by an ammeter and sent in one or the other direction through the coils with the aid of a reversing switch. The test coil has its terminals attached to a ballistic galvanometer, as is shown in the figure. This test coil fits loosely in its place and an elastic cord keeps it pulled against the test bar, so that if the movable section is pulled out the test coil will be snapped out sidewise clear of the whole apparatus.

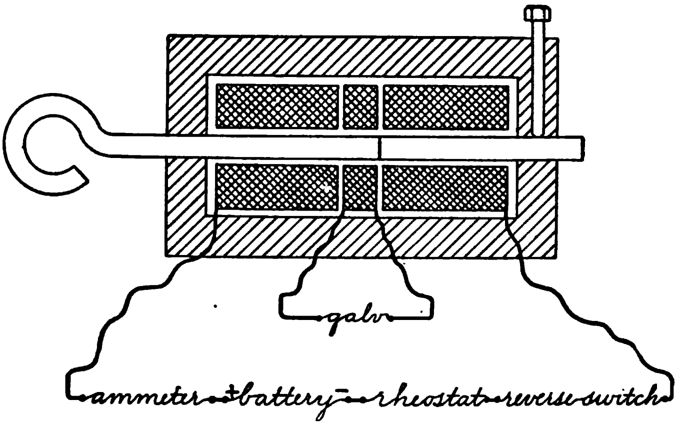

FIG. 281.

In making the test the exciting current is adjusted by the rheostat to the desired value in the regular way, the test bar handle pulled so that the test coil snaps out and the resultant galvanometer deflection is noted. As the test coil cuts the whole flux present when the handle was pulled the galvanometer deflection is a measure of the flux. The formula connecting the two is $B = K\frac{R\theta}{an}10^8$, the significance of the symbols being as before.

The magnetizing force, H, is calculated from the number of turns in the exciting coil and the strength of the current flowing through it as usual $\left(H = \frac{4\pi nI}{10l}\right)$.

In this divided bar method, correction must be made for the fact that, as the test specimen does not fit closely within the exciting coils, many lines of force pass through the test coil that do not flow through the specimen. The value of this correction is easily determined by making a preliminary measurement, using a non-magnetic test bar in place of the regular specimen.

The Hopkinson method assumes that the magnetic resistance of the yoke is so small that the length of the magnetic circuit is the length of the bar between the yoke faces. It also assumes that the magnetic resistance between the test bar and the yoke is negligible.

Neither assumption is rigorously correct and the method can hence be used only when approximate determinations are all that are required.

The Drysdale Permeameter.

A great objection to most of the devices for the measurement of permeability is that it is necessary to prepare special test specimens. Where these are made from lots of sheet metal such as is used in the construction of transformers and armatures, the specimen can as a rule be safely taken as a fair representative of the character of the lot. When, however, the test is to be made on cast metal, either iron or steel, such as enters into the construction of dynamos and motors, a test bar cast from the same pouring as the frame itself cools so much more quickly than the rest that the physical character of the metal is changed, and this affects the magnetic qualities very seriously. To cut a piece out of the casting is both expensive and unreliable, as if a fin-like projection is left to be machined off it will cool much more rapidly as would a separate test bar.

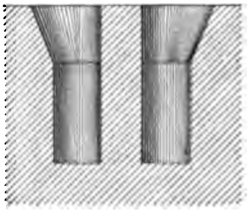

FIG. 282.

A device to overcome these objections has recently (see "Proceedings of the American Institute of Electrical Engineers," November, 1901) been devised by Drysdale. A special drill is used with which a hole is drilled in the mass of the material to be tested, leaving a cylindrical central core, as shown by the cross-sectional illustration given in Fig. 282. A tapered iron plug carrying at its lower extremity a pair of coils of insulated wire is arranged to fit in this hole and when pushed in place, as shown by Fig. 283, forms a magnetic circuit in which the central core left is energized by one of the coils, the other coil being for connection to a ballistic galvanometer, as in the case of all tests of this kind. The return magnetic circuit is through the surrounding body of the mass of metal under test, and through the testing plug.

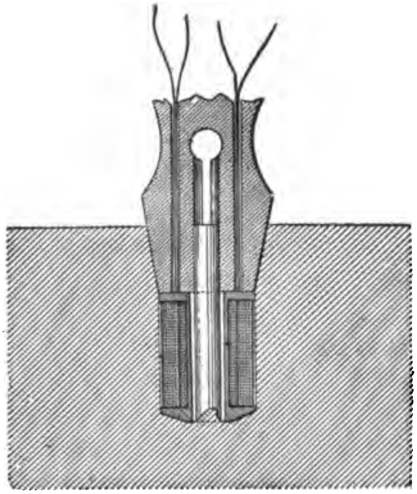
FIG. 283.

Connections are made, as in Fig. 284, and the various galvanometer throws corresponding to the reversals in the exciting current with different values of that current are plotted in the regular way.

In order to have a complete self-contained commercial apparatus, the batteries, the rheostat for varying the strength of the exciting current, the reversing switch, the ammeter for measuring current strength, and the ballistic galvanometer are all built into one case, as shown in Fig. 285, a compartment being added to receive the test plug and the cords making connection with same. The ammeter, *A*, is calibrated in amperes, and the ballistic galvanometer, *B*, is made with a needle swinging over a scale instead of a light spot and is calibrated directly in gausses.

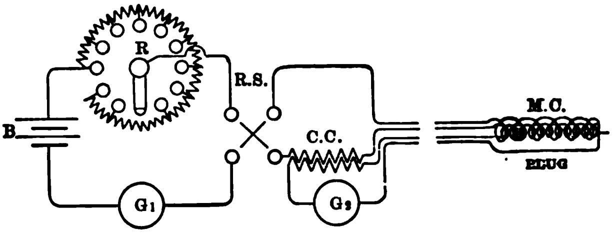

FIG. 284.

It is advisable to make the test at three or four different points in the mass of metal under examination, to be sure that no error has been introduced because of drilling into an unexpected flaw.

When necessary to restore the original condition of the magnetic circuit as fully as possible, a soft iron plug can be machined which will fit in the opening left by the drill after the test is completed, and if this is solidly driven home but little difference need be expected.

The length of the test bar is short, but the character of the contact made by the testing plug is exeptionally good and of large area, so that for high densities such as are used in practice, the results obtained can probably be relied upon with confidence.

The Quantometer.

Where ballistic test methods are used in determining the permeability of large masses of iron, some difficulty arises in employing an ordinary ballistic galvanometer, as the magnetic flux does not instantaneously attain its proper value when the current strength is changed to a new amount. As has been explained in the chapter on ballistic galvanometers, these give correct indications only when the duration of the applied current is so small as compared with the period of swing of the instrument that the former has all passed before the galvanometer needle has a chance to make a sensible deflection. The time required for the attainment of the maximum flux value in a large mass of metal may be as high as thirty or even sixty seconds, which is far too great as compared with the eight to twenty seconds period of the ordinary ballistic instrument.

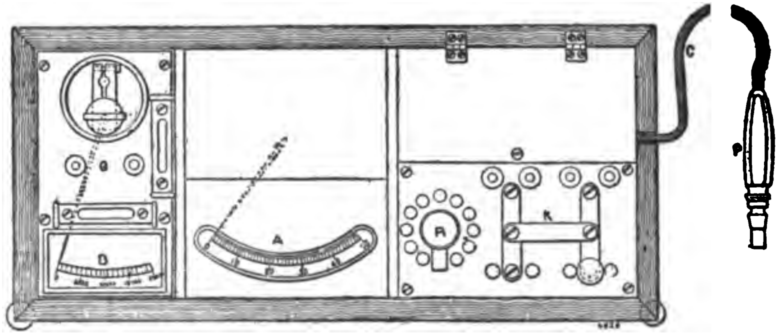

FIG. 285.

To overcome this difficulty, the "quantometer" has been suggested.

The quantometer is a galvanometer whose deflections are proportional to the quantity of electricity passed through it in spite of this long-time lag. It consists of a d'Arsonval galvanometer with a pivoted coil, like the instruments described on pages 156 to 161, but in place of the volute springs which oppose the coil motion it is equipped with fine filaments of silver or strips of phosphor bronze such as are used for galvanometer suspensions and which are disposed so as to offer no appreciable resistance to the coil motion. The windings are on a short-circuited metallic frame like that which serves to dampen the indications of the d'Arsonval instruments mentioned.

Without going into the theory of the instrument, it may be stated that with an apparatus of this nature the deflections are proportional to the quantity of electricity that flows on the assumption that the pivot friction is negligible, the restraining force of the conducting strips *nil*, and the duration of the current practically zero. A correction can, however, be applied to allow for the fact that none of these conditions is rigidly correct, and this feature admits of the use of the apparatus for the purpose named. (See *London Electrician*, Dec. 26, 1902.)

TRACTIONAL METHODS.

A magnet with its one pole in contact with a block of magnetic material attracts the block with a force expressed by the formula $p = 2\pi J^2 S$, in which S is the cross-sectional area of the pole face. From this the permeability of a given specimen can be determined if the magnetizing force, H, is known, and the latter can be calculated from the strength of the current flowing and the number of turns of the magnetizing coil by the formula $H = 4\pi\, n\, i$ (for a long coil) already given.

The formula expressing the value of the permeability then is

$$\mu = \sqrt{\frac{8\pi p}{H^2 s}} + 1.$$

Thompson Permeameter.

One of the earliest permeability measuring instruments depending in principle on this tractive force between a magnetized bar and a mass of magnetized material is the Thompson permeameter. As is shown in Fig. 286, it consists of a heavy rectangular yoke of iron, having a hole bored through one side, through which the test rod passes. The point on the inner surface of the opposing yoke against which the test bar rests is carefully machined off to have a perfectly smooth surface, and the test bar end is likewise treated. It is advisable to have the latter made slightly conical. The magnetizing coil wound on a brass tube surrounds the specimen and is itself so inclosed by the yoke that practically all of the lines of force flow through the iron circuit. There is no pull on the test rod where it passes through the upper member of the yoke, as the direction of the lines of force there is at right angles to it. By means of a spring balance whose upper ring is attached to some hook that can be gradually lifted, the pull required to separate the test specimen from the lower leg of the yoke is read off and the value of the magnetizing current simultaneously read by means of an ammeter.

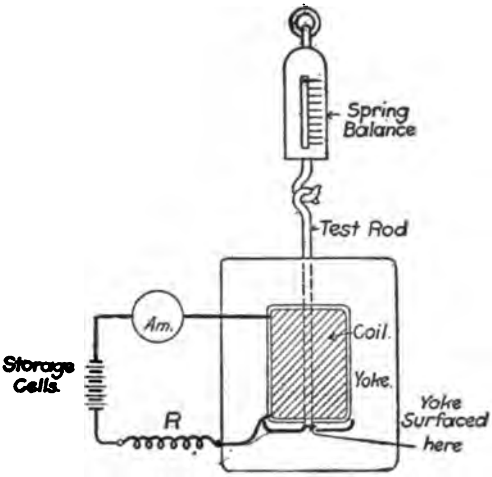

FIG. 286.

Thompson gives the following formula for the permeability:

$$(1)\quad B = 1317\sqrt{\frac{P}{A}} + H$$

$$(2)\quad B = 156.9\sqrt{\frac{P}{A}} + H.$$

In this, P is the pull in pounds in the first formula or in grams in the second, and A the area of contact of the test bar in square inches for the first formula and in square centimeters for the second. If the above are compared with the first equation giving the portative power of a magnet as above, they will be found to be substantially alike.

Several sources of error exist in this apparatus which are of such magnitude that it is not suitable for work of laboratory accuracy. It can, however, be used for demonstration purposes, and serves fairly well as a comparison instrument for comparing the permeabilities of a standard bar and an approximately similar unknown one at high flux densities.

The sources of error in the tractional permeameter are: The variable air gap where the bar passes through the hole in the yoke; the uncertainty of the contact between the lower end of the bar and the portion of the yoke on which it rests; the increasing leakage at the lower end of the bar with increasing magnetization, which leakage lines are not effective in increasing the force resisting separation; and the fact that the square root of the pull is involved in the formula which makes a small error in observation of the spring balance or in the calibration of the same, be a larger and larger per cent as the pull and therefore the magnetizing force decreases.

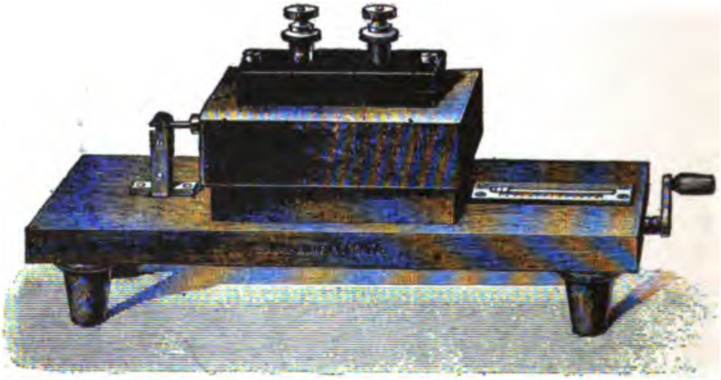

FIG. 287.

The last objection has so much weight that in practice the instrument cannot be used at all for the determination of permeability at low values of magnetizing current.

Comparative values of specimens of metal for commercial use can, however, be quickly measured by tractional permeameters, more particularly as these are generally worked at high magnetic densities.

A commercial permeameter is shown in Fig. 287, where a spring put in tension by turning the hand crank shown measures the force required to separate the specimen from the yoke.

Another tractional permeameter is shown in Fig. 288. Here sand is allowed to flow through the pipe, *T*, into a bucket, *P*, until the test specimen is torn away, whereupon the flow of sand is at once cut off and the weight subsequently ascertained.

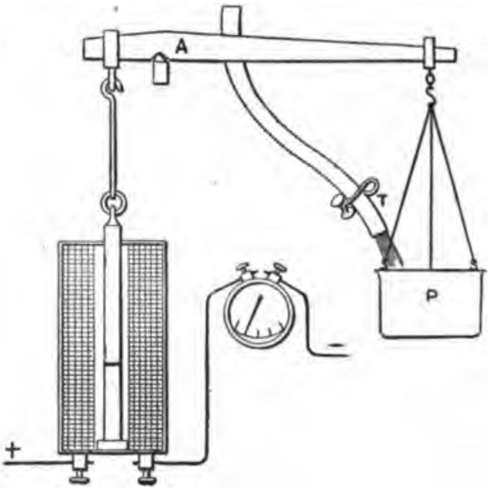

FIG. 288.

Ewing Balance.

In this instrument for measuring permeability by tractional force, an effort is made to eliminate the error due to the variable contact between the test specimen and the mass of metal closing the magnetic circuit by the expedient shown in Fig. 289. The test bar, *E*, is made circular in section as usual, and one of its ends rests in a V-shaped notch cut in one end of the iron spool about which the magnetizing coil, *B*, is wound, the other end resting on a rounded surface at the other end of the spool, as shown at *a*. The contact between *E* and *a* is necessarily a point, being the contact between two cylindrical surfaces at right angles to each other.

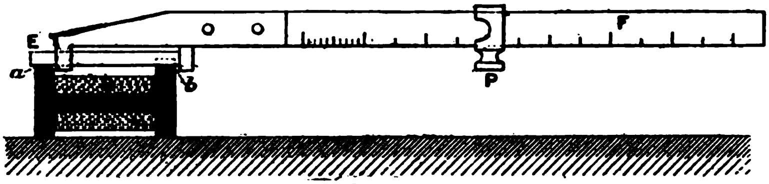

FIG. 289.

The V-shaped depression in which the end of the specimen *E* rests forms a kind of a hinge, so that when a lifting force is applied by the steel yard arrangement, *F*, *a* alone is raised. The force tending to tear the test specimen away from the magnetizing block is, of course, obtained by sliding the weight, *P*, out along the graduated arm of the steel yard.

In the commercial use of this device the current strength is not fixed by means of an ammeter, but a standard bar is first inserted, and the current varied until it just lets go for a predetermined position of *P*. The test bar is then substituted for the standard and the position of *P* which causes this to be pulled away, is noted. The steel yard is graduated directly in gausses and forms a convenient although somewhat crude arrangement for some workshop tests.

ATTRACTIONAL METHODS.

Du Bois Magnetic Balance.

In this instrument the test specimen, *D*, Fig. 290, is usually made a rod about 15 centimeters long. By means of clamps its ends are brought into close contact with heavy iron pole pieces, *P* and *P*, and the magnetic circuit is completed through these, the air gaps, *E* and *E*, and the heavy yoke, *F*. The magnetizing solenoid, *B*, surrounds the specimen. *F* is provided with a pair of knife edges located opposite to one another at the point, *A*, the peculiar distribution of metal shown by the figure being such that the yoke is balanced around *A* by the weights of the two ends. When current is passed through *B* the force of magnetic attraction at each of the faces, *E* and *E*, is evidently the same, but as the pull through the left-hand gap acts on a longer lever arm, the yoke, *F*, will tend to descend at that end.

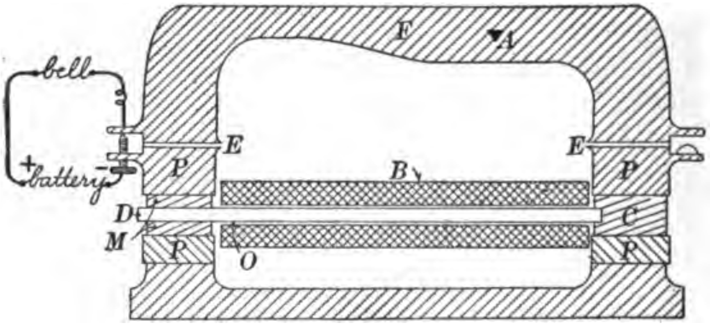

FIG. 290.

This force is balanced by moving the small sliding weight shown in Fig. 291 along the top of the yoke. Limiting stops are placed at each end of the yoke, one of them, as is shown to the left in Fig. 290, being usually provided with a pair of platinum contacts connected in circuit with a battery, and a galvanometer or bell, so that if that yoke end descends appreciably below the normal position, a warning is instantly given.

The attraction of the pole pieces on the yoke varies as the square of the flux through the magnetic circuit, and for a given magnetizing current the graduated scale alongside of which the movable weight slides may therefore be calibrated directly in gausses, the proper allowance for the reluctance of the pole pieces, the air gaps, and the yoke having first been experimentally determined and allowed for.

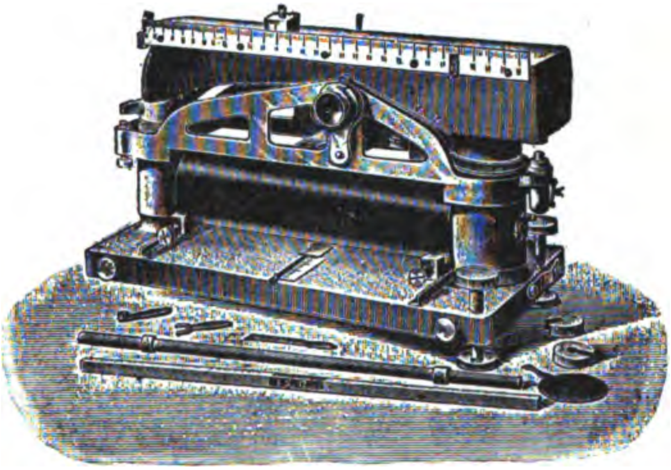

FIG. 291.

The reluctance of the air gaps in this instrument is so great as compared with that of the resistance of the rest of the circuit that small variations in the resistance of the joints between the test specimen and the pole pieces introduces no material error.

DEFLECTIONAL METHODS.

If a known current is passed through the movable coil of any of the d'Arsonval types of instruments previously described, the deflection of the needle attached thereto will be in proportion to the strength of the magnetic field in which the coil works. The flux that forms this field is, for a given strength of current through a solenoid surrounding an iron core to whose ends are attached the pole pieces between which the coil swings, proportionate to the permeability of the core. Instruments for the measurement of permeability based on this principle may conveniently be termed of the deflectional type.

Koepsel Permeameter.

This prominent instrument based on the above deflectional method is shown in section in Fig. 292. The test bar, *E*, is placed within the magnetizing coil, *B*, and firmly clamped in place by means of thumb screws to eliminate as far as possible errors due to the joints. The heavy iron pole pieces, *JJ*, embrace the movable coil, *b*, and to the latter is attached a pointer which swings over a scale graduated directly in gausses. In making a test current of a known value is sent through *b* and the deflection corresponding to different strengths of current through *B* noted. The complete apparatus is illustrated in Fig. 293, the batteries being shown behind the instrument and the rheostats for regulating the strength of the current through the magnetizing coil and the moving coil respectively to the right

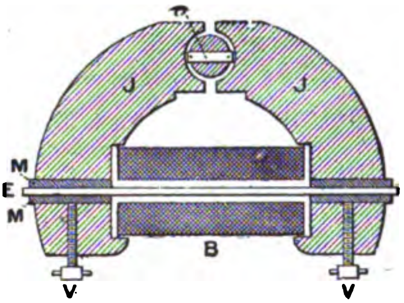

FIG. 292.

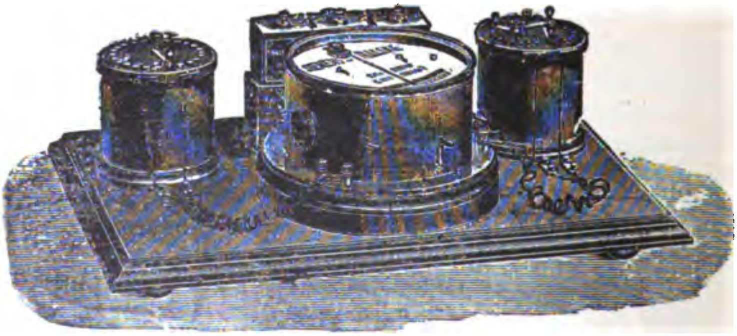

FIG. 293.

and left of it. The batteries supply the current for *b* only, that necessary for *B* being drawn from a separate source, usually storage batteries, and measured by a separate ammeter.

Carpentier Permeameter.

This instrument shown diagrammatically with its accompanying connections in Fig. 294, and in perspective in Fig. 295, is somewhat similar to the Koepsel device, but the flux through the heavy iron yoke pieces that complete the magnetic circuit is measured in another way. As is shown in Fig. 294, a small rectangular gap is left at the points of junction of the two yokes, in the upper one of which there is freely suspended a short magnetic needle. When a flux passes through the yoke the needle of course tends to place itself parallel to the lines, and the needle attached thereto which can be seen inside of the little rectangular box on top of the apparatus in Fig. 295 is deflected. By turning the knurled head shown in the same figure a spring is wound up, which as in the electro dynamometer (see page 165) introduces a measureable opposing force and brings the needle back to its original position again. The angle of twist of the knurled head required to bring the index to the zero mark is for each value of the magnetizing current, a measurement of the flux through the yokes, and the permeability of the test specimen can therefore be determined by reference to a calibration curve which accompanies the apparatus.

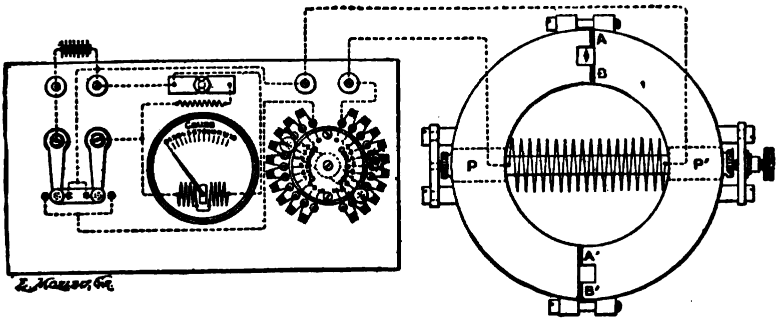

FIG. 294.

BRIDGE METHODS.

Various magnetic analogues of the Wheatstone Bridge have been proposed and constructed from time to time. The originator of the plan seems to have been Ewing, whose bridge is shown in Fig. 296. Two bars of identical dimensions are employed, one of them, *A*, being a standard, and the other the one whose permeability is to be measured. The ends of these bars are clamped into heavy iron yokes, *CC*, and a pivoted magnetized needle, *a*, placed between their extremities serves to indicate whether these yokes are magnetized. The bar, *b*, shown is a short permanent magnet which is used to give directive force to the pivoted needle.

A and *B* are surrounded each with its own magnetizing coil, the two being connected in series, but opposed so that the direction of flux through the one is opposite to that in the other. The number of turns around the standard specimen is fixed, but that around *B* is variable by means of a contact arm whose end can be moved over a row of contacts connected to different turns of the winding. This contact arm device is equipped with auxiliary resistances, so that each time a coil is cut out of the magnetizing circuit an equivalent resistance is added to the circuit, so that the strength of the current flowing remains uniform.

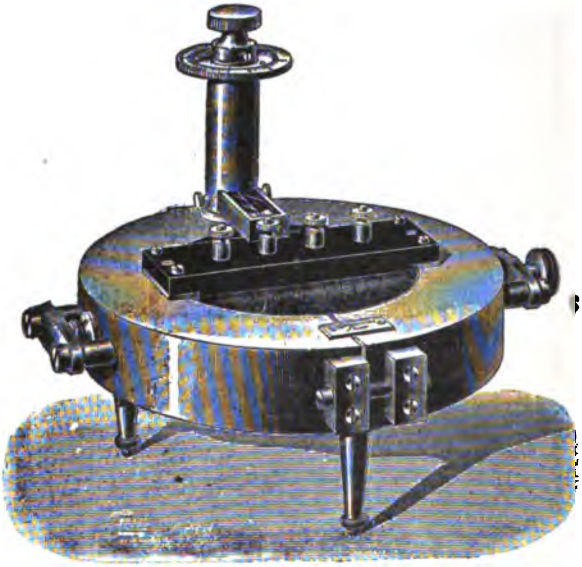

FIG. 296.

When the flux through each specimen is the same, the path of the lines of force is evidently along one and back through the other, none being compelled to flow through the yokes and across the gap. No deflection of the needle, *a*, thus means that the fluxes are the same. In practice the number of turns surrounding the test bar is varied until the needle, *a*, no longer shows a permanent deflection with the current flowing in one direction or the other, whereupon it is known that the fluxes furnished by the two specimens are alike since they neutralize each other. Their permeabilities are hence in the ratio of the turns. To obtain the complete permeability curve the strength of the current being used must be measured by means of an ammeter and successive readings made for different values.

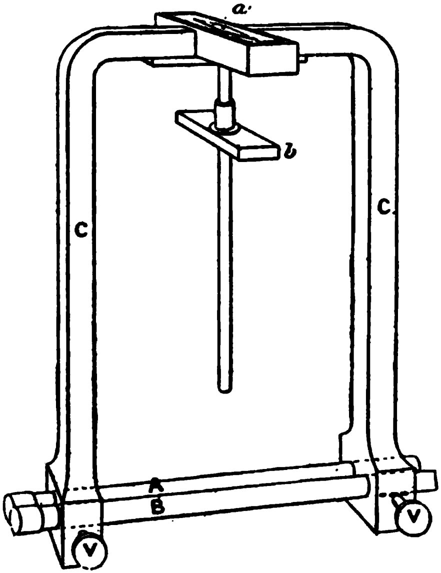

FIG. 296.

MISCELLANEOUS METHODS.

The large errors introduced by the variable value of the contact between a test specimen and the heavy iron yokes used in most permeameters has led to many attempts to devise some satisfactory method that will give results which are independent of this element.

One of the early ones is due to Ewing and operates as follows:

Referring to Fig. 297, *A* is a standard bar and *B* the one to be measured. Holes are drilled in the iron yokes, *C* and *D*, into which these bars fit snugly, the contact being made as solid as possible by means of the clamp screws. Solenoids through which are passed the magnetizing current surround both test specimens and are made of a length that just fits between *C* and D with these in the position shown in the figure. An exploring coil surrounds one of the solenoids and the value of the flux through B is found in terms of that through A by a method similar to that used in the Rowland test before described. The magnetic circuit in this case evidently includes the reluctances of the bars A and B plus that of the yokes, C and D, plus that of the four joints between the bar ends and the yokes. After making a determination with the yoke, D, located as illustrated, the clamp screws holding it to the bars are loosened and the yoke slides along to a new position. The test is repeated there, and from this and the preceding one the induction in the test specimen is calculated. As the contacts between the yoke, C, and the two bars are undisturbed their reluctance and that of the yoke is eliminated. The same thing holds good of the reluctance of the yoke, D, so that the result is correct if the magnetic resistance of the joints between A and D and B and D is the same in the first position of D as in the second.

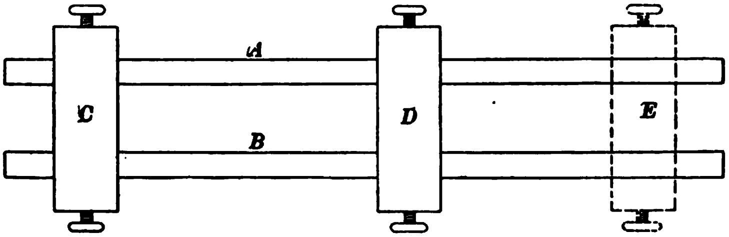

FIG. 297.

It is unfortunate that this last assumption is not entirely valid and that the arrangement therefore gives permeability values which while amply close for practical purposes at high magnetic densities are not sufficiently exact for accurate work or at low densities.

Picou Permeameter.

In this instrument devised by Picou and modified by Armagnat, the method of eliminating the errors due to the variable resistance of the magnetic joints is entirely different.

Referring to Fig. 298, the test specimen, b, is made rectangular and may take the form of a prism of solid metal or of several layers of sheet iron such as is used for transformer and armature work. There are two yokes, B_1 B_2 respectively, which are

U shaped and between the ends of whose legs the test specimen is inserted. Magnetizing coils surround all three as shown and suitable resistances, R_1 R_2, are inserted in the yoke and test specimen circuits, so that the strength of the current flowing through them may be varied at will.

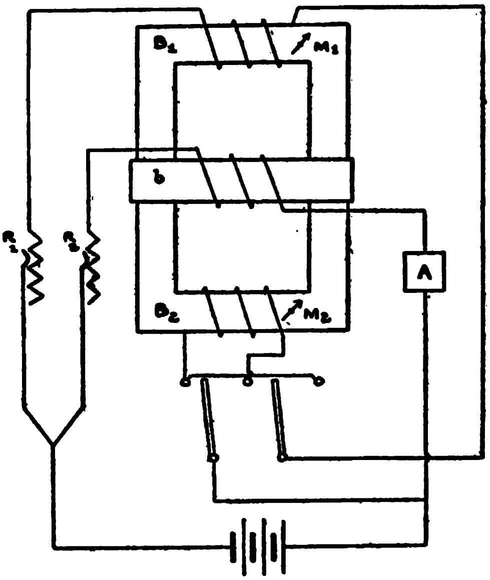

FIG. 298.

The measurement of the permeability of *b* involves two steps. First of all, current is sent through the solenoids surrounding the yokes in such a direction that the resultant magnetic fluxes form a closed path through the yokes only, as is shown by the dotted lines in Fig. 299. Under these circumstances it is clear that there is no flux through the bar, *b*, itself, and that the reluctance of the magnetic circuit is that of the material composing the yokes plus that of the four joints between the test specimen faces and the yoke ends, plus the reluctance of those portions of the length of the test bar, lettered *c* and *a* respectively, in Fig. 299.

Suppose that under these conditions the flux through the circuit is ascertained by making a ballistic test or in any other convenient manner. The permeability of the circuit can then be calculated from the magnetizing force due to the measured current through the exciting solenoids in the ordinary way.

The electrical connections are then changed so that the direction of the current in one or the other of the exciting solenoids is reversed, with the result that the flux directions through B_1 B_2 are opposite, as shown in Fig. 300. The magnetic circuit for each yoke is then completed through the test specimen, and as the reluctance of this circuit is greater than the first by that of the specimen for its length, *e*, the flux through both B_1 and B_2 is lessened. By passing current through the solenoid surrounding the test specimen in the proper direction a magnetomotive force is set up, which can be adjusted by manipulating the rheostat, R_2, Fig. 298, until the flux through B_1 and B_2 becomes again what it was under the conditions in Fig. 299.

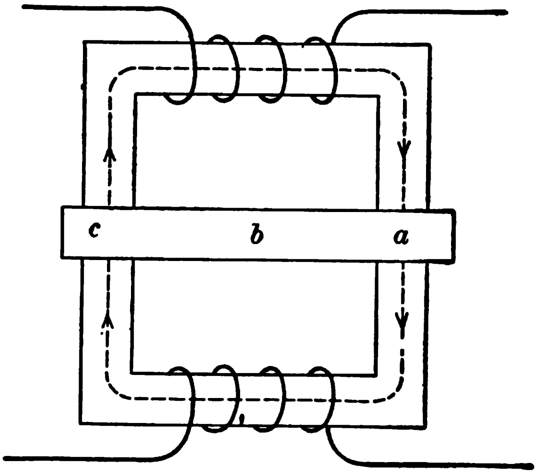

FIG. 299.

The reluctance of the test specimen may then be calculated directly from the strength of the current that must be passed through its surrounding solenoid to bring about the above state of affairs, for the magnetomotive force that the coil must supply is just that required to force the known flux through the specimen, that required to overcome the reluctance at the joints having been accounted for in the first measurement. Knowing the strength of the current around *b* and the number of turns in its solenoid, the magnetizing force, and therefore finally the permeability, may be determined direct.

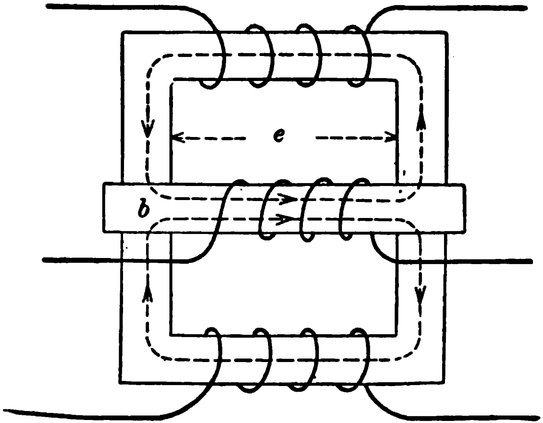

FIG. 300.

Owing to the great superiority of zero methods of measurement over methods involving values of deflection, considerable thought has been devoted to modifying this Picou apparatus to bring it into this category. As a result it is now generally

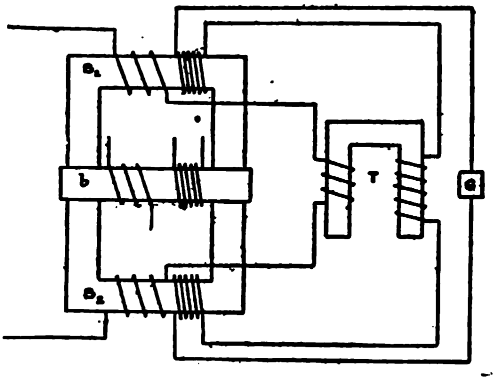

FIG. 301.

supplied arranged as follows: As shown in Fig. 301, a fine wire winding acting as an exploring coil surrounds each yoke and the test specimen. An auxiliary transformer, *T*, is also employed which is energized by being placed in series with the magnetizing windings surrounding the yokes and whose transformation ratio may be manually adjusted at will. The secondary circuit of the auxiliary transformer is completed through the two

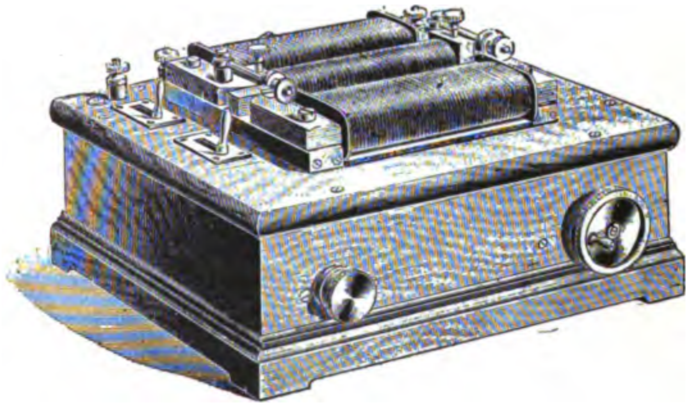

FIG. 302.

exploring coils on the yokes, connections being made so that the E.M.F.'s induced therein are opposite to that induced in the coils. It can readily be seen that by suitably adjusting the transformation ratio of T the effect on a galvanometer, G, inserted in the coil circuit may be made zero; the fact that equilibrium has been thus attained must be carefully established by several reversals of the direct magnetizing current.

To determine the flux in the bar, b, after the electrical connections are changed so that the magnetic circuit is completed through it, a special commutator is employed, which cuts the solenoids of B_1 and B_2 out of circuit at the same time that b's solenoid is inserted. The discharge through b's test coil circuit is passed through a ballistic galvanometer, whose scale may be calibrated directly in gausses.

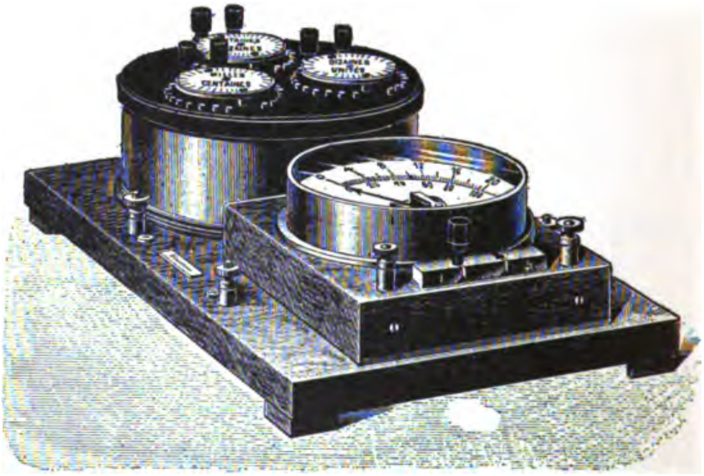

FIG. 303.

The portion of the instrument containing the two yokes with their coils plus the commutator and reversing switch is shown in Fig. 302, that of the portion of the apparatus including the rheostat and galvanometer being illustrated by Fig. 303.

It is claimed that the results obtained with this device are of the highest accuracy and that the elimination of the resistance at the joints is so far successful that a practically identical set of readings is obtained for a given stack of sheet iron strips for the order in which they are first placed in the apparatus and that which they show when subsequently removed, mixed up at random, and then replaced.

Burger Permeameter.

This device, while probably not capable of giving as accurate results as the preceding, is in quite extended use and has the advantage of giving the results very rapidly. In it the test bar is cut in half and mounted on a heavy iron yoke in a manner somewhat similar to that employed in the Hopkinson divided bar apparatus. The magnetizing coil surrounds the specimen in the same way also, but instead of having a snap coil in the gap between the bar ends, a bismuth spiral is inserted, as is shown in Fig. 304. The variations in electrical resistance of this spiral form a measure of the strength of the field in which it is placed (see page 350) and hence of the permeability of the rod under test.

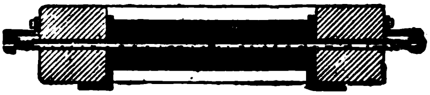

FIG. 304.

As made by Hartmann and Braun, the Burger permeameter is made one self-contained piece of apparatus, as is illustrated in Fig. 305, and includes the yoke with its clamps, magnetizing coil, and bismuth spiral; two slide-wire bridges, one to make temperature corrections and the other for measuring the resistance of the spiral; a galvanometer for use with the bridge; an ammeter for measuring the exciting current; a combination galvanometer and battery key for the bridge, and a reversing switch for the energizing circuit.

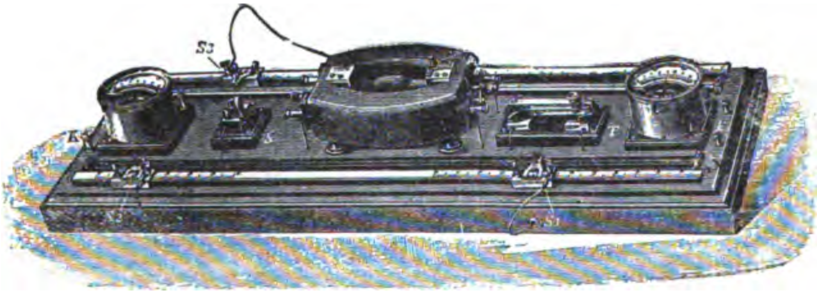

FIG. 305.

CHAPTER IV.

HYSTERESIS.

If we start with a completely demagnetized iron specimen and draw its permeability curve by any of the methods just given the curve will, as has been explained, take the form shown by the solid line in Fig. 306. If after the maximum desired value of *H* has been been attained the exciting current is decreased step by step, the values of *B* corresponding to those of *H* will no longer coincide with those found in the initial test, but will give a set of readings which when plotted will form the dotted curve in the same figure. If the direction of *H* is now reversed, the value of *B* will continue decreasing until it comes to zero and will then itself reverse in direction until

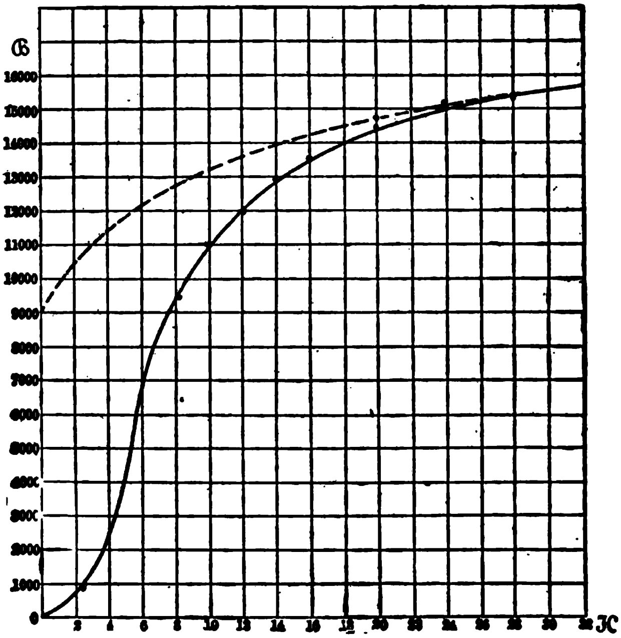

FIG. 306.

a maximum negative value is attained which will be found equal to the positive value corresponding to the same maximum positive value of H. If H is then brought back to zero, reversed, and then increased, again a similar curve will be given which will join the first when H has reached its first positive maximum value. The curves form a closed figure shown in Fig. 307, which is known as the hysteretic loop. It will be retraced as often as the magnetizing force is made to go through the same cycle of changes in strength. The shape of the loop depends not only on the metal under test, but its physical condition, being, for instance, much more elongated and of larger area for a hard tempered piece of steel than for one cut from the same specimen that was subsequently carefully annealed. It can be shown that if the value of B in Fig. 307 is expressed in lines of force, and that of H in tens of amperes, the area of the hysteresis loop is the energy in ergs required to force the metal to overcome the cycle of changes.

Also it has been found that for a given specimen and form of wave of the exciting current, the area of the loop is the same whether the successive reversals in flux succeed one another with the lowest frequency found in commercial apparatus or the highest frequency.

The predetermination of the amount of energy consumed by hysteresis is a most important requirement in the design of much electrical machinery.

MEASUREMENT OF HYSTERETIC LOSSES.

Method of Plotting Curves.

A very obvious method of determining the hysteretic loss is to draw the complete loop from successive observations made with differing magnetizing forces by any of the permeability measuring plans spoken of, and then to obtain the area of the resultant loop with the aid of a planimeter. Just as obviously, however, this method is exceedingly tedious because of the large number of observations required, and it is therefore seldom used in the workshop.

Wattmeter Method.

The energy consumed in the hysteretic cycle may be measured very simply by using a sensitive indicating wattmeter. For this test the specimen is surrounded with a magnetizing coil and the energy expended therein measured, first with the specimen removed, and afterward with it in position. The first reading gives the energy required to overcome the resistance of the magnetizing coil itself, and the second that energy plus that expended by hysteresis and eddy currents. As it is difficult to determine the latter separately this meter test is usually used only when it is possible to obtain the specimen in the form of thin sheets, which may be electrically insulated from one another by varnishing or otherwise, thus practically eliminating the eddy current loss.

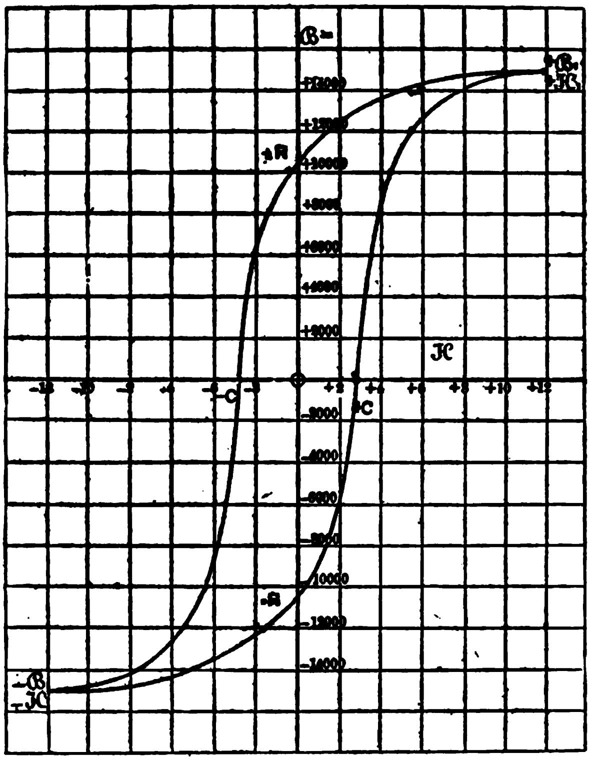

FIG. 307.

Instead of connecting the wattmeter in the usual way, it is advisable to have two windings over the specimen, one of wire through which the magnetizing current flows, and the other of fine wire insulated from the first, and in which there is generated by the alternating flux an E.M.F. that is applied to the potential circuit of the wattmeter. This eliminates the error due to the energy loss in the coil. Connections of this kind are shown in Fig. 308, where there is added also an ammeter and a voltmeter. The two latter instruments are useful for determining the magnetomotive force and the flux respectively.

Ewing Hysteresis Meter.

The hysteretic loss in a given specimen is the same whether the alternations in the field strength are caused by rotating it through a field or holding it stationary and reversing the direction of the current through the exciting coil. It is also the same whether the specimen is held stationary and the field rotated or *vice versa.*

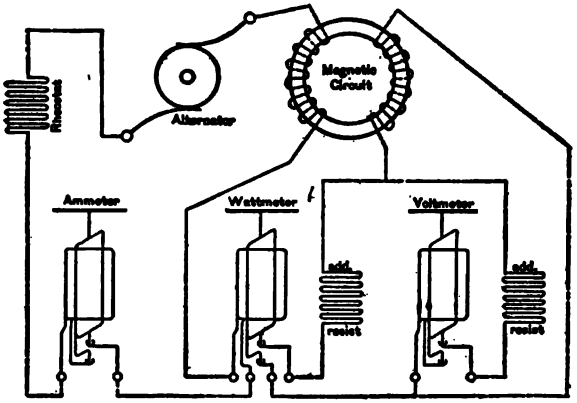

FIG. 308.

One of the best known hysteretic loss meters is the Ewing, which is based on the latter principle and constructed as shown in Fig. 309. In it a C-shaped permanent magnet is supported by knife edges on agate bearings, and between its polar extremities there is placed a clamp to hold the test specimen. This whole clamp may be rapidly rotated by means of the hand wheel, and when this is done the reaction between the field of the specimen and that of the magnet tends to carry the latter along in the same direction, this motion being opposed by suitable counterweights and indicated by a needle sweeping over a stationary scale. To the lower part of the magnet is fixed a flat vane dipping into an oil bath which dampens the indications.

Two standard specimens are supplied with each instrument and the deflections that these give are noted before any test is started. These two values are used to establish a curve showing the relation between the deflection and the hysteretic losses, so that when the unknown specimen is inserted the hysteresis loss can be found from the deflection by referring to the curve.

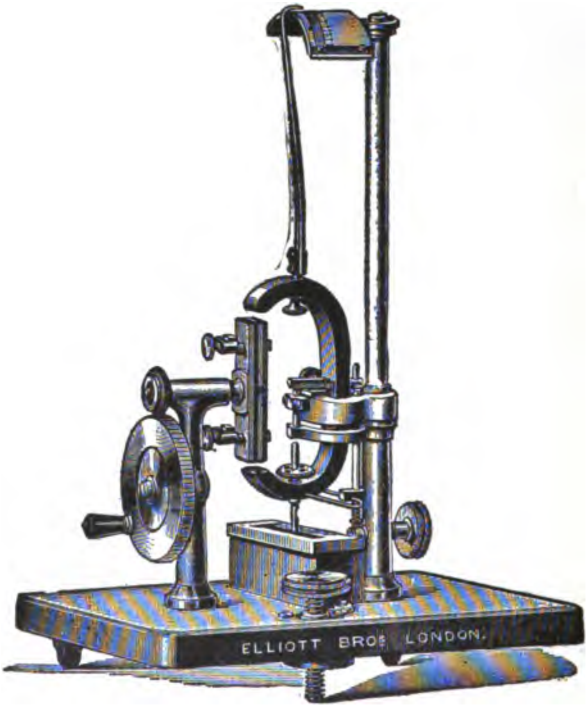
ELLIOTT BROS LONDON.

FIG. 309.

The sample must be laminated in order to avoid eddy currents, but it is claimed that the thickness to which they are piled up has such a small effect that within the limit allowed by the clamps no correction need be applied.

Professor Ewing has recently determined that the hysteretic loss in the standard test specimens does not remain constant indefinitely, and it is hence advisable to primarily determine the value of that of the standard by some other method if the apparatus is to be used for exact determinations. This refinement is however not necessary in workshop practice, because comparitive results are as a rule all that is desired.

Blondell Hysteresis Meter.

In this instrument, which is shown in section in Fig. 310, the test specimen is made in the form of a ring which is secured to a support that can be rotated about the central axis of the device. The tendency to rotate is balanced by means of the spring shown, and a needle attached to the frame carrying it is brought back to a zero mark by turning a knurled head as in a dynamometer. The rotating magnetic field is supplied by the U-shaped magnet, and its torque as indicated by the position of the torsion head is a measure of the hysteretic loss.

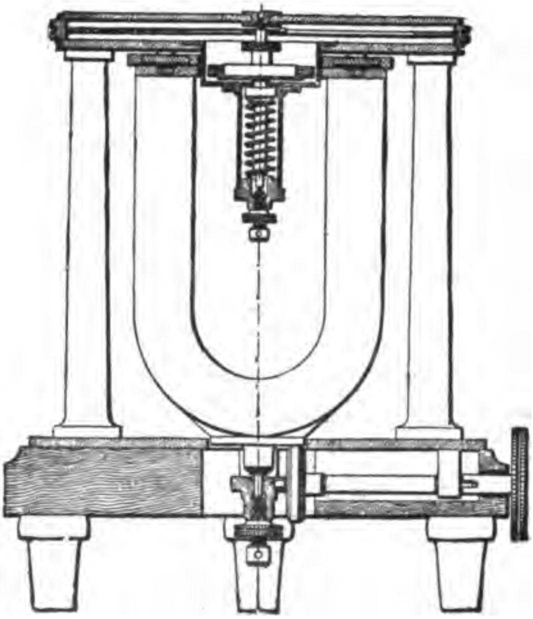

FIG. 310.

Holden Instrument.

Another hysteresis meter, used by the General Electric Company and employing a cylindrical test specimen in a rotary field, is shown in Fig. 311. The magnet is here an electromagnet, current being passed through its winding with the aid of two collector rings like those of an alternating current generator. The arrangement for measuring the torque of the sample is the same dynamometer spring affair, the values of the torque being read off from the position of a movable index relative to a fixed scale.

In this instrument provision is made also for the measurement of the flux, this being done as follows: A coil surrounds but does not touch the test ring and rotates with it. It has its terminals connected to a two-part commutator, so that it delivers direct current to a pair of binding posts that are connected to the brushes. A voltmeter attached to the binding posts then shows the magnetic induction as the number of turns in the exploring coil, the cross-section of the test specimen, the speed of rotation of the magnet, and the resistance of the circuit comprising the voltmeter, test coil, and connections are all known. The test coil feature is a most convenient one, as by its aid the induction in the specimen can be read in each instance and of course readily adjusted to any desired value by varying the strength of the exciting current. It is claimed that the most important reason for not adopting the Ewing plan of employing a rotating permanent magnet in place of the electromagnet is that with the former results obtained on specimens of iron of widely different character were not correct.

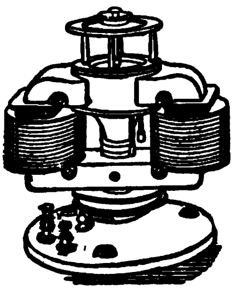

FIG. 311.

Searle Method.

A very elegant method for measuring the hysteretic loss for a single magnetizing cycle has been proposed by Searle, and involves the use of an instrument that is practically a ballistic wattmeter. As is shown by the diagrammatic sketch in Fig. 312, the test specimen, E, is placed inside of a solenoid, the series coil, of the wattmeter being connected in series with this winding. Another coil surrounds the first, and to its terminals is connnected the potential coil of the wattmeter.

To the terminals, A and B, of the magnetizing coil there is connected a reversing commutator, so that the current sent through it and whose value is measured by an ammeter can be suddenly reversed in direction. The electro-motive force induced in the secondary winding is proportional to the rate of change

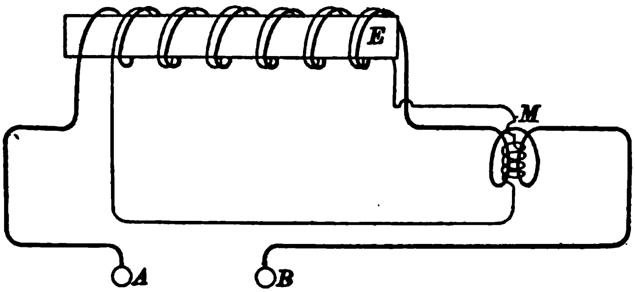

FIG. 312.

in flux through the core, that is, to $\frac{dB}{dt}$. The current through the primary winding at this instant is Hdt, so that the couple deflecting the wattmeter is $Hdt\ \frac{dB}{dt}$. This integrated shows that the deflection of the instrument is proportional to HB, that is to say, to the hysteretic loss.

It is, of course, assumed that the reversal is made so quickly that the whole cycle has been completed before the galvanometer has a chance to make a sensible deflection.

APPENDIX.

The following list is intended to serve as a general guide to those who desire to ascertain where they may procure instruments and devices of the types described in this volume, or to obtain from the makers thereof more detailed information as to construction or operation than has found place in a treatise of the necessarily general nature of this one. It is not contended that the list is complete, in fact it would hardly be feasible in many instances to ascertain and record each maker of each form of device, but it is thought that it will be found accurate as far as it goes and should certainly serve a useful purpose. In those cases where the manufacturer is located abroad, the endeavor has been made to give the name of the United States representative of the line as well as his own so as to enable those interested to promptly communicate with the nearest authoritative source.

The schedule is arranged in the order of the serial numbers of the illustrations to facilitate reference thereto. Where an illustration is not mentioned by a number in the list and is not simply diagrammatic or illustrative of a principle, it may usually be taken for granted that the apparatus is of a special or laboratory character, built to order only, and about which a specialist in fine instrument building should hence be consulted if it is desired to procure the actual apparatus.

LIST OF ABBREVIATIONS EMPLOYED.

A. E. G.	Allgemeine Elektricitats Ges., Berlin, Germany.
B. Co.	Bristol Company, Waterbury, Conn.
C. & A.	Chauvin and Arnoux, Paris, France.
C. & Co.	Crompton and Company, London, England.
C. O.	C. Ollivetti, Milan, Italy.
C. S. I. Co.	Cambridge Scientific Inst. Co., Cambridge, England.
D. E. M. Co.	Duncan Electric Mfg. Co., Lafayette, Ind.
D. M. Co.	Diamond Meter Co., Peoria, Ill.
E. B.	Elliott Bros., London, England.
E. D. Co.	Electro Dynamic Co., Bayonne, N. J.
E. E. M. Co.	Edison Electric Mfg. Co., Orange, N. J.
E. V. B.	E. V. Baillard, New York, N. Y.

F. P. Co.	Foote, Pierson & Co., New York, N. Y.
F. W. E. Co.	Fort Wayne Elect. Co., Fort Wayne, Ind.
G. E. Co.	General Electric Co., Schenectady, N. Y.
G. I. Co.	General Inc. Arc. Light Co., Pittsfield, Mass.
H. & B.	Hartmann and Braun, Frankfort, A. M.
J. C.	Jules Carpentier, Paris, France.
J. G. B.	Jas. G. Biddle, Philadelphia, Pa.
K. & W.	Jas. White, Glasgow, Scotland.
L. M. P.	L. M. Pignolet, New York, N. Y.
L. & N.	Leeds and Northrup Co., Philadelphia, Pa.
M. & E.	Mayer and Englund, Philadelphia, Pa.
M. & R.	Machado and Roller, New York, N. Y.
M. B. F. Co.	Meyers Break Finder Co., Syracuse, N. Y.
N. E. I. Co.	Norton Electrical Inst. Co., Manchester, Conn.
O. W.	Otto Wollff, Berlin, Germany.
Q. Co.	Queen and Co., Philadelphia, Pa.
R. W. P.	R. W. Paul, London, England.
S. & H.	Siemens and Halske, Berlin, Germany.
S. E. Co.	Sangamo Electric Co., Springfield, Ill.
S. E. I. Co.	Syracuse Electrical Inst. Co., Syracuse, N. Y.
S. E. M. Co.	Stanley Electric Mfg. Co., Pittsfield, Mass.
W. & G.	Willyoung and Gibson Co., New York, N. Y.
W. E. Co.	Western Electric Co., Chicago, Ill.
W. E. M. Co.	Westinghouse Elect. & Mfg. Co., Pittsburg, Pa.
Wag. E. M. Co.	Wagner Elec. Mfg. Co., St. Louis, Mo.
West. E. I. Co.	Weston Elec'l Inst. Co., Waverly Park, N. J.
Whit. E. I. Co.	Whitney Elec'l Inst. Co., Penacook, N. H.

MAKERS OR AGENTS.

Fig. No.	
1	J. C.
3	L. & N., F. P. Co., W, & G., Q. Co., S. & H., O. W.
4	E. B.
5	W. & G., Q. Co., L. & N., F. P. Co.
6	“ “ “ “
7	“ “ “
10	Q. Co., J. G. B., K. & W.
11	J. C.
14	Q. Co., W. & G., L. & N., F. P. Co.
15	West. E. I. Co.
16	Q. Co., W. & G., L. & N., F. P. Co.
20	Q. Co., J. G. B., K. & W., H. & B.
21	“ “ “ “
22	“ “ “
24	L. & N., Q. Co., W. & G., J. C.
29	L. & N., Q. Co., W. & G., F. P. Co.
31	“ “ “ “
32	M. & R., C. & A.
36	Q. Co., W. & G., L. & N.

Fig. No.					
37	L. & N.,	Q. Co.,	W. & G.,	W. E. Co.,	F. P. Co.
40	"	"	"	"	"
40A.	C. S. I. Co.				
44	L. & N.,	Q. Co.,	W. & G.,	W. E. Co.,	F. P. Co.
45	"	"	"	E. V. B.,	"
47	"	"	"	"	"
48	H. & B.				
49	H. & B.				
51	L. & N.,	M. & R.,	C. & Co.		
52	Q. & Co.,	L. & N.,	W. & G.,	F. P. Co.	
53	M. & R.,	C. & Co.			
54	J. G. B.,	C. S. I. Co.			
55	"	"			
56	M. & R.,	C. & Co.			
57	L. & N.				
58	O. W.,	L. & N.,	Q. Co.,	W. & G.	
59	L. & N.				
61	Q, Co.,	L. & N.,	W. & G.		
67	"	"	"	F. P. Co.,	Whit. E. I. Co.
68	"	"	"		
69	Whit. E. I. Co.				
71	O. W.				
73	E. V. B.,	L. & N.,	Q. Co.,	W. & G.	
75	L. & N.,	Q. Co.,	W. & G.		
76	Whit. E. I. Co.				
80	E. B.				
88	M. & R.,	C. & A.			
91	L. & N.,	Q. Co.,	W. & G.		
92	"	"	"		
93	"	"	"		
95	"	"	"		
98	Whit. E. I. Co.				
99	"				
100	"				
104	Q. Co.				
106	Whit. E. I. Co.				
107	L. & N.,	Q. Co.,	W. & G.		
116	J. C.,	L. M. P.			
118	Whit. E. I. Co.				
119	West. E. I. Co.				
120	Whit. E. I. Co.				
121	E. E. M. Co.				
122	G. E. Co.				
124	"				
125	"				
126	Q. Co.,	L. & N.,	W. & G.,	F. P. Co.	
127	H. & B.				
129	A. E. G.,	K. & W.,	W. E. M. Co.		

Fig. No.	
130	K. & W.
131	"
132	G. E. Co.
133	Q. Co., N. E. I. Co., W. E. Co.
137	H. & B., S. E. M. Co.
138	" "
139	Whit. E. I. Co.
140	"
143	G. E. Co., W. E. M. Co., Wag. E. M. Co.
145	Whit. E. I. Co., A. E. G., H. & B.
147	R. W. P., M. & R.
149	H. & B.
150	A. E. G.
151	G. E. Co.
152	"
153	W. E. M. Co.
154	"
155	F. W. E. Co.
156	West. E. I. Co.
157	S. E. I. Co., G. E. Co.
158	C. & A., M. & R.
159	G. E. Co., W. E. M. Co.
160	" "
161	West. E. I. Co., Whit. E. I. Co.
162	West. E. I. Co.
169	Whit. E. I. Co.
170	West. E. I. Co.
173	W. E. M. Co., A. E. G.
174	" "
179	West. E. I. Co., Whit. E. I. Co.
185	L. & N., Q. Co., W. & G., F. P. Co.
187	" " " "
189	" " " "
194	" " " "
200	" " "
206	" " "
208	"
209	"
212	C. S. I. Co., W. & G., J. G. B.
213	W. & G.
214	H. & B., M. & R.
215	" "
216	W. E. M. Co.
217	A. E. G.
218	H. & B.
221	G. E. Co., W. E. M. Co.
222	" "
223	E. D. Co., West. E. I. Co.

Fig. No.	
238	M. B. F. Co.
241	B. Co.
242	C. & A., M. & R.
243	“ “
244	G. E. Co.
245	H. & B., S. & H.
246	C. S. I. Co., J. G. B.
248	C. O.
249	“
250–1	West. E. I. Co.
257	Whit. E. I. Co.
260	G. E. Co., D. M. Co., D. E. M. Co.
262	G. E. Co.
265	S. E. Co.
271	G. I. Co.
274	H. & B.
287	J. C.
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